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MONTHLY WEATHER REVIEW

First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: Domestic, \$3.50; Foreign, \$4.50; 30¢ per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

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(Continued on inside back cover)

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The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

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ESTIMATION OF FRICTION OF SURFACE WINDS IN THE AUGUST 1949, FLORIDA HURRICANE

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[Manuscript received June 3, 1953; revised March 4, 1954]

ABSTRACT

The equations of motion are adapted for use in computing the tangential and normal components of friction in a model hurricane. Values of the components of friction are estimated from surface data of the August 1949 Florida hurricane. The computations are based upon mean pressure and wind profiles describing the front and rear portions of the storm, within 28 to 70 miles from the center, as it moved through the Lake Okeechobee region. The tangential component of friction appears to be greater than the normal component in the region to the rear of the center, while in advance of the center the opposite is generally observed. All friction curves show a continuous increase of friction with wind speed.

INTRODUCTION

In cooperation with the Corps of Engineers, U. S. Army, the Hydrometerological Section of the United States Weather Bureau has been investigating surface winds of hurricanes, with particular interest in the region of Lake Okeechobee, Fla. One phase of the investigation was concerned with the forces resisting surface winds. Although the frictional forces elude exact measurement, their importance to the behavior of surface winds is readily apparent. A familiar approach to the problem of computing friction is through the theory of the mixing length, assuming that the mixing length can be determined and that the velocity distribution, especially along the vertical, is known. This method is discussed in detail by Rossby and Montgomery [1]. Since the hurricane data available to the Section were marked by an absence of upper air observations, further consideration of the mixing-length theory was necessarily eliminated. The equations of motion, therefore, were developed in a form suitable for use with hurricane surface data to compute friction. Their development and the results subsequently obtained are presented in this paper.

THE EQUATIONS OF MOTION

The equations of horizontal motion may be written

$$\frac{dv_s}{dt}=-\alpha\frac{\partial p}{\partial s}-F_s$$
$$\frac{v_s^2}{r_s}+fv_s=-\alpha\frac{\partial p}{\partial n}-F_n \tag{1}$$

where v_s is the speed along the path, s; r_s, radius of curvature of s, is positive for cyclonic curvature; t is time; f the Coriolis parameter; α the specific volume; p the pressure; n, a normal to s, is directed opposite to the Coriolis force; and F_s and F_n are the components of friction, tangent and normal, respectively, to the path. For convenience in a study of friction the above equations are rewritten

$$F_s=-\alpha\frac{\partial p}{\partial s}-\frac{dv_s}{dt}$$
$$F_n=-\alpha\frac{\partial p}{\partial n}-\frac{v_s^2}{r_s}-fv_s \tag{2}$$

Friction is defined here as the sum of all forces which are

due to friction and viscosity. In addition to the friction arising from flow over a rough ground surface, it includes the effects of lateral eddy viscous forces, whether accelerative or retardative, imposed by adjacent air currents.

METHOD OF CALCULATING THE FRICTION IN A MODEL HURRICANE

The solution of equations (2) for a model hurricane, characterized by a steady state of mean flow, circular symmetry, and constant latitude, is given in this section.

It is seen from the working model, shown in figure 1, that

$$\begin{aligned} ds &= -dr/\sin\theta \\ dn &= -dr/\cos\theta \end{aligned} \qquad (3)$$

where r, the distance from the center, is directed outward, and θ is the deflection angle of the wind as measured from the normal of r to the tangent of the trajectory s. Since the mean flow has been assumed to be steady,

$$\frac{dv_s}{dt} = v_s \frac{\partial v_s}{\partial s} \qquad (4)$$

In accordance with Yates [2], the radius of curvature of a spiral may be written

$$r_s = r\frac{dr}{dq} \qquad (5)$$

where q, a normal to the tangent of the spiral, is drawn from the origin as shown in figure 1. From figure 1 it is seen that

$$q/r = \cos\theta \qquad (6)$$

Differentiating equation (6) with respect to r and substituting the result into equation (5) gives

$$r_s = \frac{1}{\dfrac{\cos\theta}{r} - \sin\theta\dfrac{d\theta}{dr}} \qquad (7)$$

Substitution from equations (3), (4), and (7) into equations (2) gives

$$\begin{aligned} F_s &= \left(\alpha\frac{\partial p}{\partial r} + v_s\frac{\partial v_s}{\partial r}\right)\sin\theta \\ F_n &= \left(\alpha\frac{\partial p}{\partial r}\right)\cos\theta - v_s^2\left(\frac{\cos\theta}{r} - \sin\theta\frac{\partial\theta}{\partial r}\right) - fv_s \end{aligned} \qquad (8)$$

The friction at a selected distance from the center of the model hurricane is computed by using equations (8) with values obtained from three curves showing the respective relations of pressure p, wind speed v_s, and deflection angle θ, to distance r from the center. Representative values of virtual temperature and latitude must of course be selected for evaluating the specific volume and Coriolis parameter.

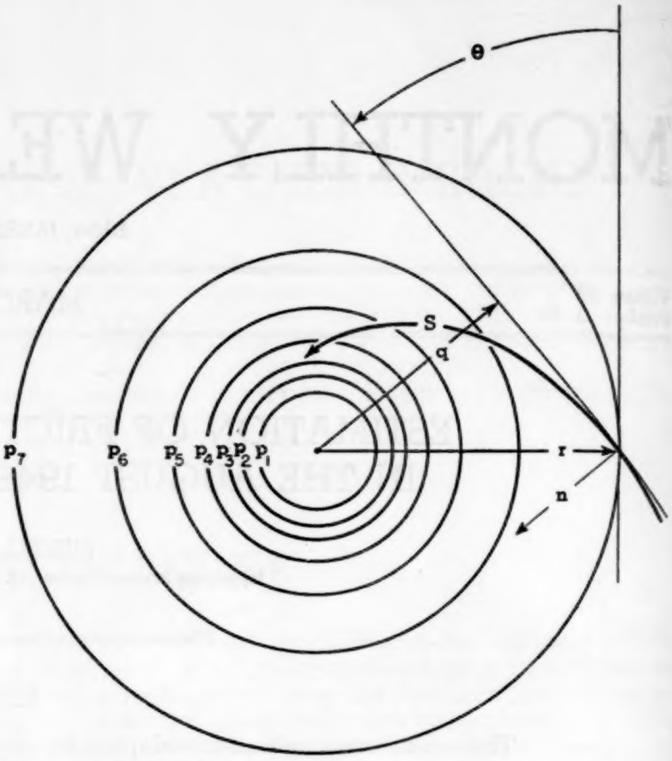

FIGURE 1.—Hurricane model.
p_i=Value of a circular isobar.
r=Distance from the center, directed positive outward.
s=Path of air particle, directed positive in the direction of motion.
θ=Deflection angle of the wind across a circular isobar.
n=Normal to s, directed opposite to the Coriolis force.
q=A normal to tangent of path, drawn from center.

INSTRUMENTATION

The Corps of Engineers maintains meteorological observation stations at seven hurricane gates on the shore of Lake Okeechobee and three wind-recording stations on steel-girder pylons within the lake. The station locations are shown in figure 2. Esterline-Angus multiple pen recorder traces of the wind speed and direction were available for the lake stations. Dines anemometers at the hurricane gates provided continuous traces of wind speeds and directions except for Hurricane Gate No. 3 where wind speeds only were available. The hurricane-gate stations also provided barograph traces. The heights of anemometers are given below in table 1. The water surface is about 14 ft. msl and the land surface 14 to 16 ft. msl.

TABLE 1.—*Anemometer height at observation stations at Lake Okeechobee*

Station	Anemometer height (ft. msl)
Hurricane Gate No. 1	58
Hurricane Gate No. 2	55
Hurricane Gate No. 3	56.5
Hurricane Gate No. 4	55
Hurricane Gate No. 5	55
Hurricane Gate No. 6	55
Port Mayaca	56
Lake Station No. 12	46.5
Lake Station No. 14	48.5
Lake Station No. 16	47.5

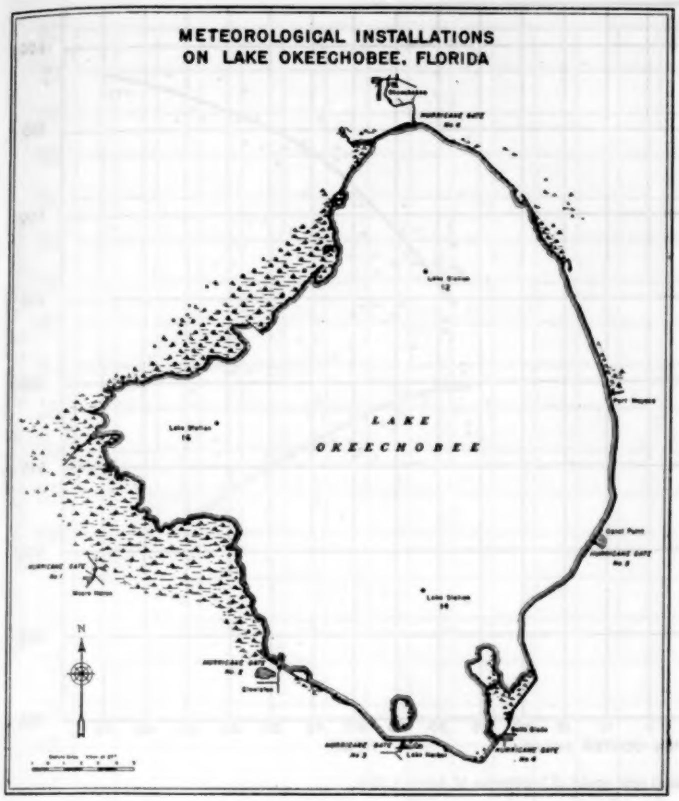

FIGURE 2.—Map of Lake Okeechobee area showing location of observation stations.

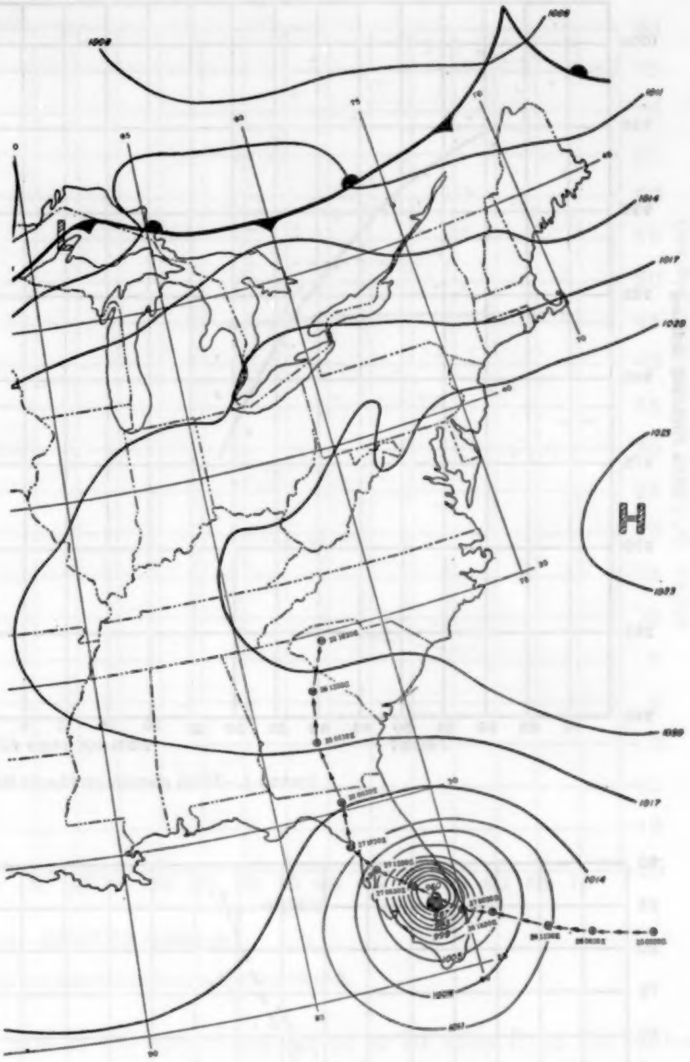

FIGURE 3.—Section of surface chart for 0330 GMT, August 27, 1949, showing current position and path of hurricane.

ESTIMATION OF FRICTION IN THE AUGUST 1949 FLORIDA HURRICANE

The method presented for calculating the friction was derived by assuming a symmetrical hurricane with steady mean flow and no variation in latitude. These assumptions were convenient in order to arrive at an exact mathematical expression for the friction. Although the assumptions may be reasonably well satisfied in nature by a quasi-stationary hurricane showing little change in intensity, no hurricane is expected to satisfy the assumptions perfectly. Because an ideal system is lacking, computed values of friction must properly be regarded as estimates.

Although the data of this hurricane were the best available to the Hydrometeorological Section, they were not entirely satisfactory. Insufficient synoptic data led to the use of observational histories of the 10 stations at Lake Okeechobee. The basic data were extracted at 10-minute intervals from recording charts. Because of the fluctuations in wind speed and direction, each wind datum was extracted as a 10-minute average value. The deflection angles of the wind were measured with reference to circles having their origin at the rotation center. The locations of the stations relative to the hurricane center, whose path is traced in figure 3, were determined for successive 10-minute positions of the center for the times corresponding to those of the data extracted from the station recording charts. The station-location data used with the station records determined the wind speeds, deflection angles, and pressures for positions in the hurricane. Thus, each station furnished data for several positions in the front and rear portions of the storm. The data used for the front were observed during a 5-hour period as the storm moved 85 to 90 miles northwestward toward Lake Okeechobee. The central pressure of the storm remained nearly constant within the range 28.15 to 28.20 inches. The data used for the rear were observed during a 5-hour period in which the storm progressed about 65 miles in the region beyond the Lake and the central pressure rose from about 28.20 to 28.40 inches.

The data observed at each 10-minute position of the storm are plotted in figures 4–6. For any given station these plotted points will of course be spaced farther apart the faster the movement of the storm center and the closer the station lies to the path of the center. Mean curves based only upon these plotted points would therefore be biased in favor of those stations which, because of their locations, provided a greater number of observations

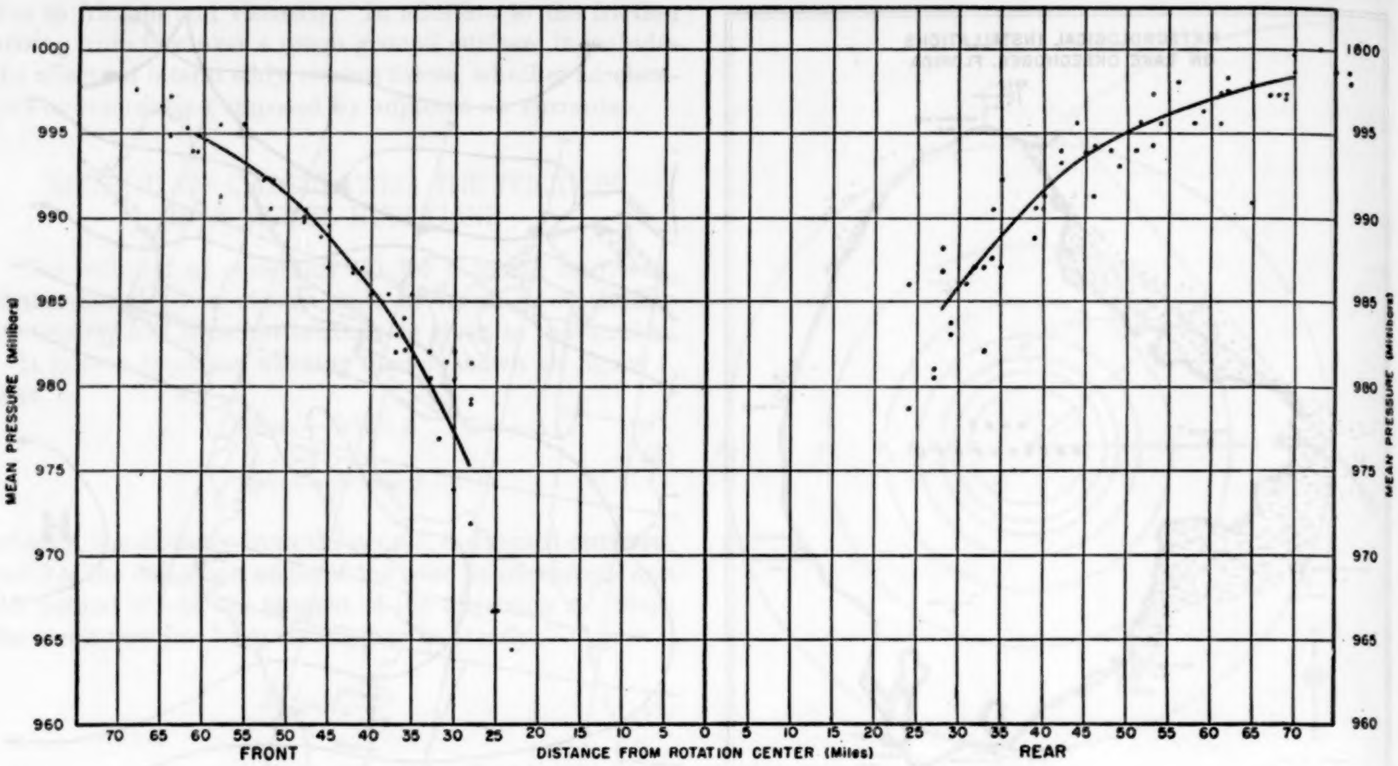

FIGURE 4.—Mean pressure profiles for front and rear areas of hurricane of August 1949.

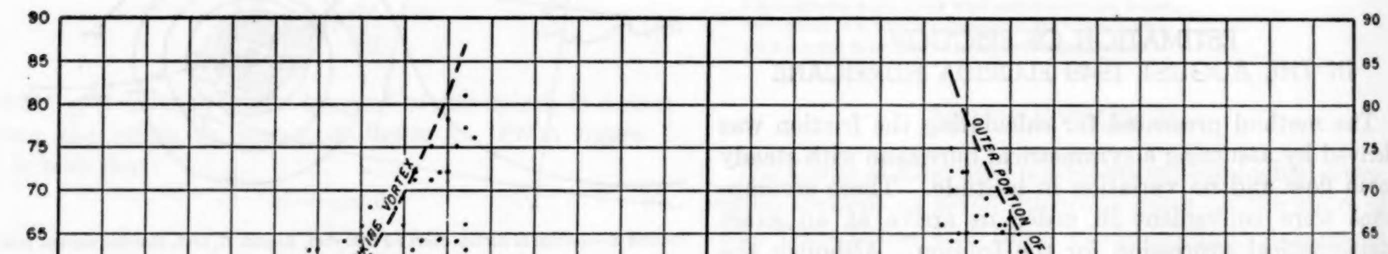

FIGURE 5.—Mean wind speed profiles, each compared with a Rankine Vortex, for front and rear areas of hurricane of August 1949.

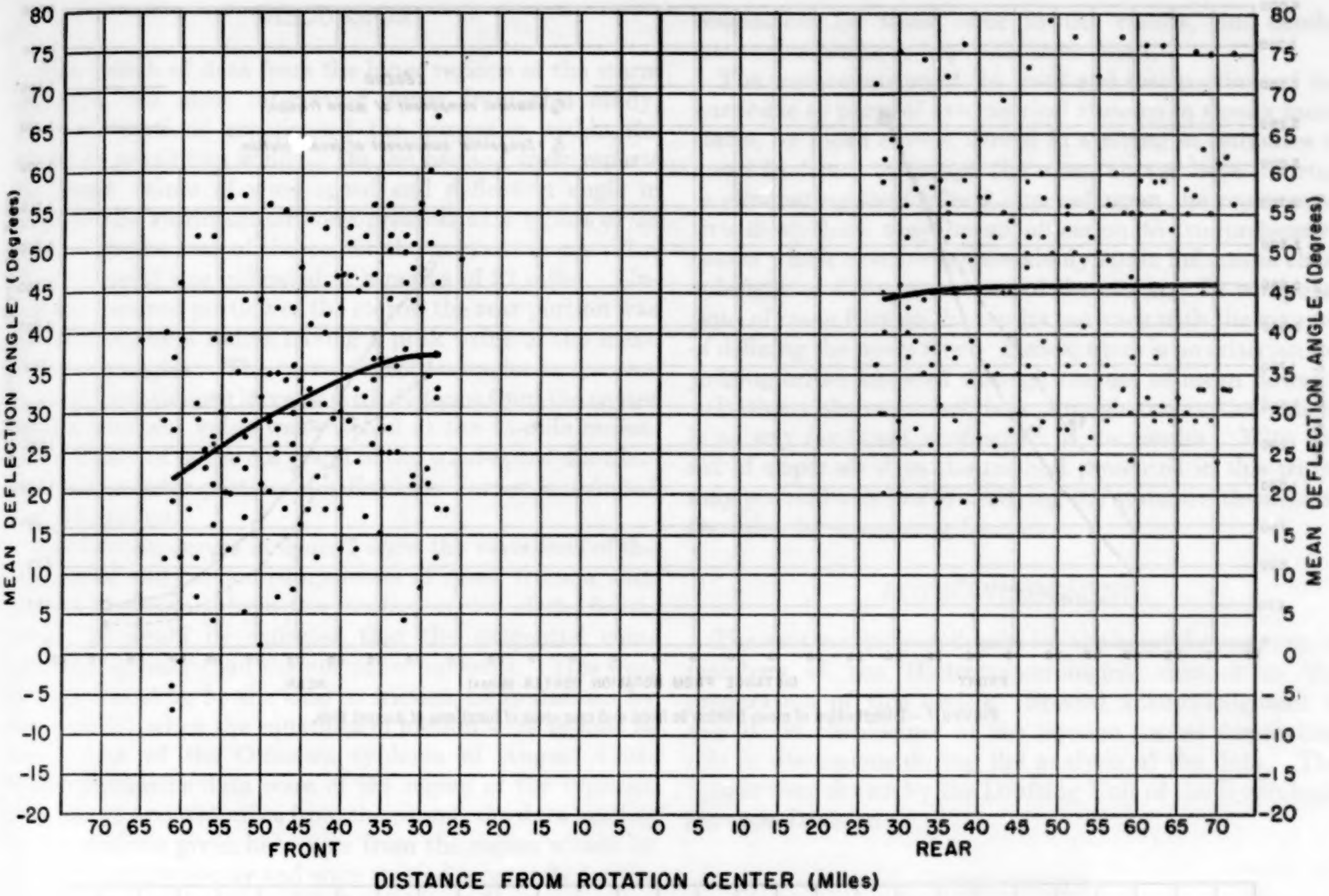

FIGURE 6.—Mean deflection angle profiles for front and rear areas of hurricane of August 1949.

within the part of the storm represented by the curves. With the purpose of allowing all stations to have equal influence on the curves, interpolations were made from a tabulation of the 10-minute observational data for each station in order that every station might be represented by data, observed or interpolated, at every mile distance from the center. During the 10-minute time intervals between observed data, changes were very small and linear interpolations within these small increments appear to be highly satisfactory. The complete tabulation of observed and interpolated data was used to compute arithmetic averages of pressure, wind speed, and deflection angle for every mile distance from the center. Thus, equal weight was given to all stations in determining the mean profiles shown in figures 4–6. Although the data of the several stations on which each of these curves is based were observed over a 5-hour period, the average times of the data corresponding to the points on a curve all fall within a period of only about 2½ hours. Since the center of the hurricane passed within 28 miles of every station at Lake Okeechobee it was possible to construct the curves for the region outside the 28-mile radius. Continuation of these mean curves within the 28-mile radius was not permitted in view of a bias introduced by the decrease in the number of observing stations with nearness to the center. Extension of the curves beyond 60 or 70 miles from the center was not possible because of the uncertain position of the center when it was located out at sea and later because of the filling which occurred after the center had moved beyond Lake Okeechobee.

It can be seen from figure 3 that the storm center moved over the northeastern part of the Lake and, hence, most of the data were from the left side of the storm. At all stations the winds were influenced by both land and water in proportions which varied with each change in the relationship of the wind pattern to the land-water distribution. The mixed influence of land and water in various proportions contributed to the scatter of observed wind values. In figure 5 the separation of points plotted for the rear of the storm into two groups according to wind speed is due to relatively large differences in the proportional influence of land and water. Since the winds were under a mixed influence, it was not possible to make a comparative analysis of pure-water and pure-land winds. By using the mean curves, figures 4–6, with equations (8), the mean friction was estimated at a sufficient number of distances from the rotation center to define the friction curves shown in figure 7. In the computations the air was considered saturated at 75° F. and the latitude was taken as 27° N.

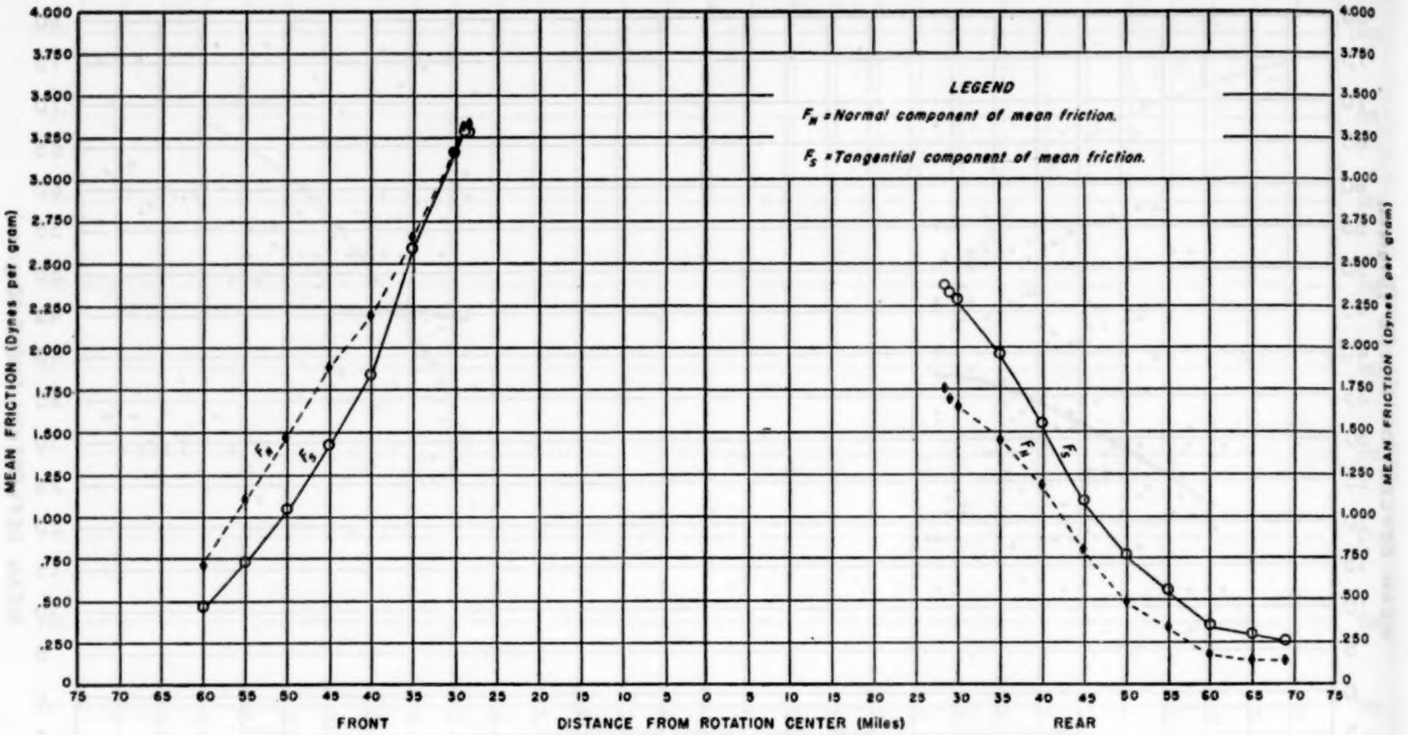

FIGURE 7.—Distribution of mean friction in front and rear areas of hurricane of August 1949.

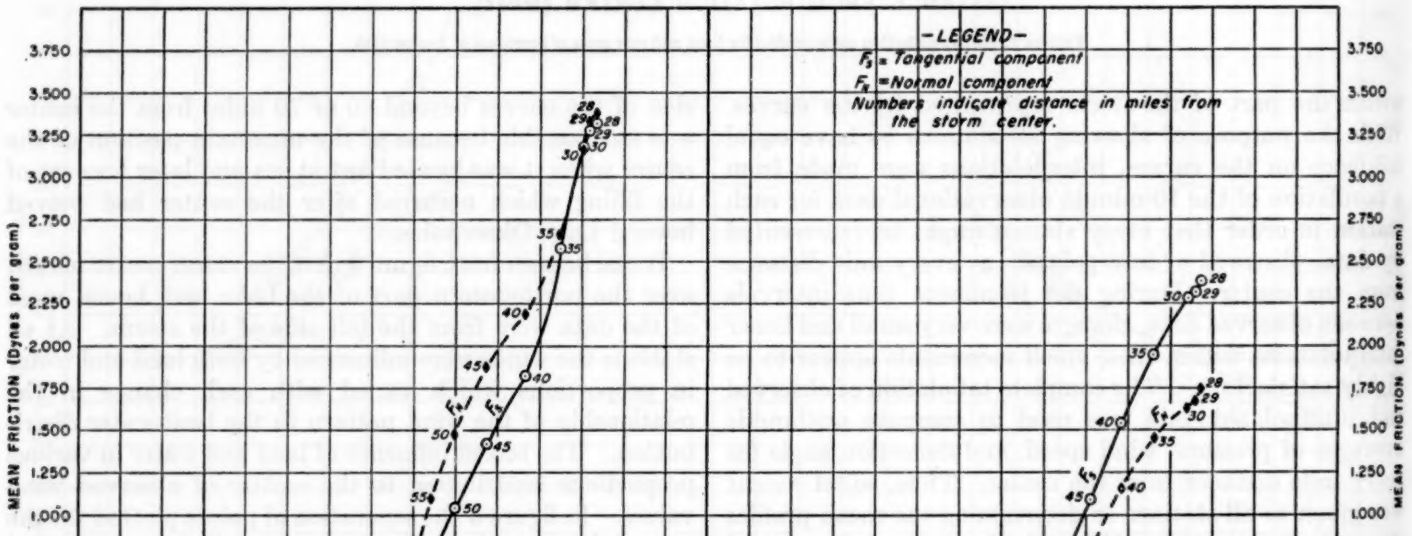

FIGURE 8.—Relations of components of mean friction to mean wind speed for front and rear areas of hurricane of August 1949.

DISCUSSION

The dearth of data from the inner regions of the storm excluded the most interesting zones from this study. Only six stations experienced the hurricane within the radius of maximum winds. On the basis of their reports the mean values of wind speed and deflection angle in front of the storm center were greatest at a radius of 25 miles. In the rear of the center the greatest mean value of wind speed was indicated at a radius of 22 miles. Unlike the forward portion of the storm, the rear portion was not marked by a radius having a peak value of the mean deflection angles. The mean deflection angles in the rear showed a continuous increase with distance from the center until a constant value was reached at the 45-mile radius. In each part of figure 5 a graph of the wind-speed distribution in the outer portion of a Rankine Vortex is included for comparison.

The friction curves in figure 7 show the variations of the tangential and normal components of mean friction with respect to distance from the rotation center of the hurricane. It would be expected that the tangential component is greater than the normal component. This was, in fact, found to be the case in friction computations by Horiguti [3], when the equations of motion were applied to mean data of the Okinawa typhoon of August 1924. While Horiguti's data were of the region of the typhoon between 62 and 435 miles from the center, the data leading to the analysis given here were from the region within 70 miles of a storm center and were treated separately for the front and rear portions of the storm. In the present analysis, the tangential component again was found to be greater than the normal component in the region to the rear of the center. But in front of the center, as shown in figure 7, the normal component generally appears to be the greater.

The relations of the tangential and normal components of mean friction to mean wind speed are presented in figure 8. Each curve shows a continuous increase of friction with wind speed. The number beside each plotted point indicates the distance from the storm center.

Errors introduced in the computations by assuming horizontal flow, constant virtual temperature of surface air, and a mean latitude are considered negligible. The subjectivity in measuring slopes of the basic curves is responsible for some error in the results, but careful measurements have kept this error small.

The representation of the front and rear portions of the hurricane as parts of symmetrical systems in steady mean states, by mean curves, served in arriving at estimates of mean friction. Although the mean curves have a virtue in eliminating local effects imposed upon the representative flow, there may be an objection to comprehensive means which obscure large-scale dynamic influences characteristic of different sectors of the storm. In computations of mean friction the results can vary with the manner of defining the mean flow. Hence, there is no criterion for judging errors incurred through the use of mean flows.

Without observational data through the vertical, there is no way for direct verification of the results. With the aid of upper air data the method presented in this paper may provide a means of verifying the standard theoretical formulae for computing friction.

ACKNOWLEDGMENTS

The writer expresses thanks for the helpful comments of members of the Hydrometeorological Section in the preparation of this article. Special acknowledgment is due R. W. Schloemer of the Section for his stimulating role in discussions during the analysis of the data. The figures were drawn by the Drafting Unit of the Hydrologic Services Division.

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3. Yosiki Horiguti, "On the Typhoon of the Far East, Part III. Winds in the Typhoon Area," *Memoirs of the Imperial Marine Observatory*, Kobe, Japan, vol. III, No. 3, June 1928, pp. 91–125 (see pp. 104–110).

THE WEATHER AND CIRCULATION OF MARCH 1954 [1]

A COOL MARCH WITH A 6-DAY PERIODICITY

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The weather during the first month of spring 1954 displayed quite a few noteworthy features. These included: a marked temperature reversal, i. e., a cool March following the warmest February of record in the United States [1]; a recurrence of Pacific blocking very similar to that of January 1954 [2]; further intensification of the Southwestern drought; and manifestation of another spring periodicity in the United States.

THE TEMPERATURE REVERSAL—FEBRUARY TO MARCH

Despite the well-known vagaries of March weather, one of the outstanding aspects of the weather this month was the widespread prevalence of below normal temperatures (Chart I–B) succeeding the warmest February in 62 years of record. While such February to March changes are not unknown, the more favored months for reversals are October to November and, less frequently, April to May. In studies of recent monthly anomaly patterns of temperature, precipitation, and height, Namias [3, 4] has shown that there has been some tendency for February–March regimes to persist, i. e., to resemble each other, rather than the contrary.

More interesting, perhaps, than this immediate aspect of low persistence is the addition of another cool March to the curious repetitions of cool March weather (in the United States) which have occurred in recent years. Weighted temperature averages for the United States show below normal temperatures during every March of the last 8 years except 1953 [5]. Moreover, this has also been true for 10 of the last 13 years (for March). Although these data seem rather impressive, a survey of the 62 years of record reveals that such runs are not too unusual. For instance, since 1893 the following March sequences were evidenced:

Below normal	10 out of 13 years (1912–24)
	9 out of 12 years (1943–54)
Above normal	8 out of 10 years (1902–11)
	7 out of 8 years (1933–40)

These data may provide a little more evidence to those seeking long-term periodic fluctuations in weather. Inspection of the outstanding sequences obviously suggests a possible oscillation with a period of the order of 30 years. This may be related to the historic Brückner cycle [6] (35 years), but the substantiation of any such connection is beyond the scope of this article.

GENERAL CIRCULATION CHARACTERISTICS

The cool temperatures of March were not unusual when examined in terms of the prevailing circulation pattern. Figure 1 shows the mean 700-mb. heights and their departures from normal for March. These points seem relevent: (1) Heights were below normal over just about all of the United States. (2) Heights were significantly above normal (maximum of 390 ft.) in the northeastern Pacific. (3) The polar vortex (80° N., 130° E.) was relatively strong (350 feet below normal) but well removed from North America.

These conditions were quite opposite to those which prevailed in February. The stronger-than-normal westerlies which then maintained over the eastern Pacific and North America were replaced by weaker-than-normal westerlies in March. Furthermore, rising heights in the northeast Pacific and Canada were accompanied at sea level by a marked decrease of cyclonic activity in the Gulf of Alaska (Chart XI), and a marked increase in the intensity of the polar anticyclone over western Canada. The latter can also be associated with the weakening and retreat of the polar vortex. These same changes were associated with sea-level departures from normal of +14 mb. in the Gulf of Alaska and +5 mb. over Saskatchewan (Chart XI inset).

The increased importance of polar anticyclones is shown by the tracks (Chart IX) of repeated thrusts of cold air from Canada into the United States. Their effect upon the temperature regime (illustrated in Chart I–B) was to produce temperatures some 6° F. below normal in Montana, with below normal anomalies extending southeastward through Florida. In the Far West temperatures were below normal mainly as a result of cold unstable maritime air associated with a deeper than normal trough in California. In small areas of the Southwest and Northeast, temperatures were above normal but only slightly so.

At upper levels, the essential characteristics of the atmospheric flow pattern were much the same as at the

[1] See Charts I–XV following p. 95 for analyzed climatological data for the month.

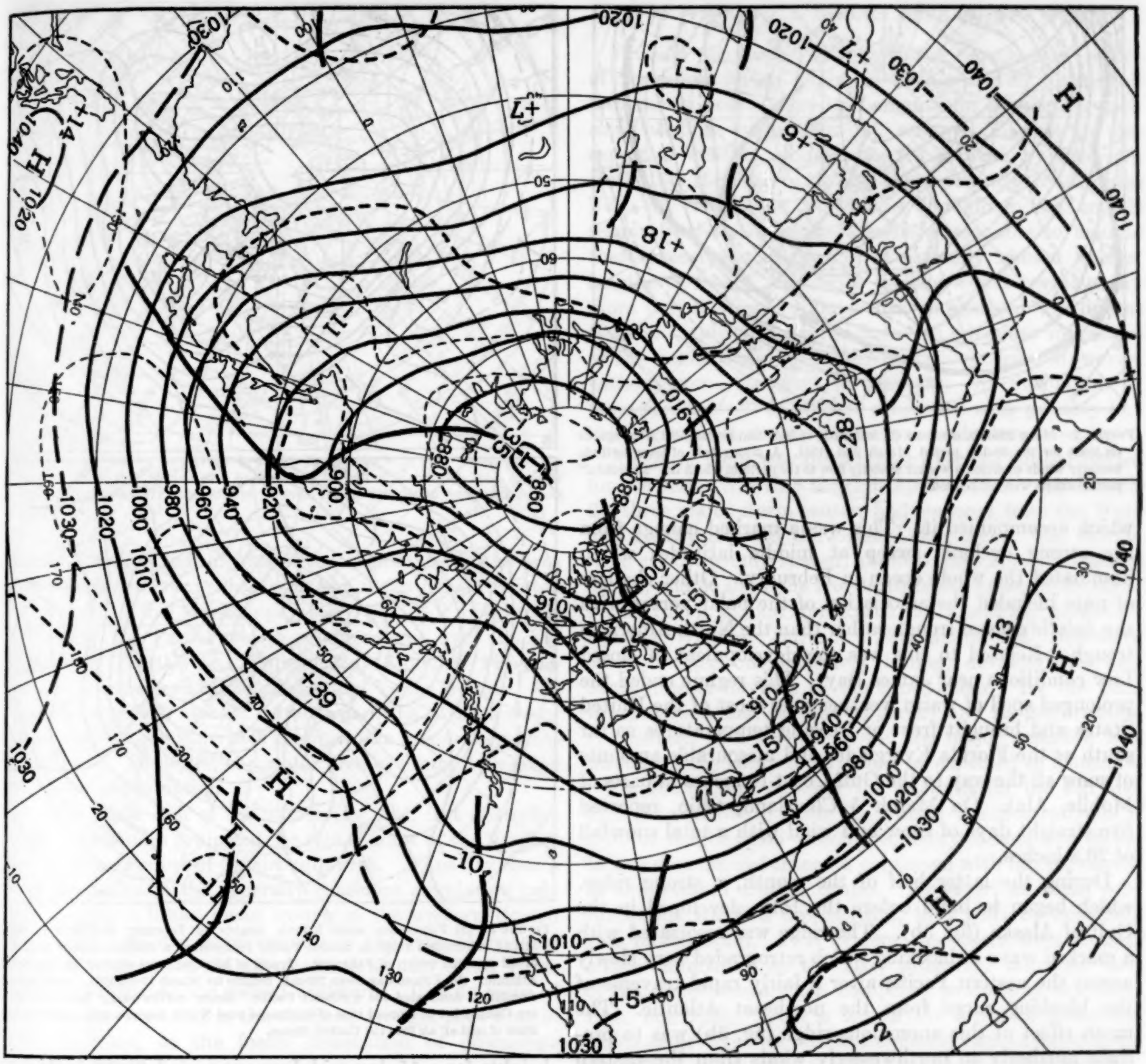


FIGURE 1.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for the 30-day period March 2-31, 1954. Note abnormal ridge (heights 390 ft. above normal) in the northeast Pacific, weaker than normal midlatitude westerlies from mid-Pacific to mid-North America, and broad zone of confluence over central United States.

surface. The eastern Asiatic coastal trough existed up through the 200-mb. level (fig. 2) and was accompanied by geostrophic wind speeds averaging 60 to 70 m./sec. around 30° N. The occurrence of strong jets in the southern Japanese Islands is quite common, but montbly averages for March are not usually so high. This wind maximum (solid arrows in fig. 2) had at lower latitudes a clearly defined trajectory from Japan through the Hawaiian Islands to the southern United States, then out across the Atlantic and through northern Africa. To the north of this circumpolar whirl the mean troughs and ridges were superimposed upon a slower westerly flow. These features can be readily associated with their 700-mb. counterparts.

The implication appears to be that there was little or nothing abnormal about the interrelation of trough-ridge features within the troposphere. Rather, that the determining factor in the cool regime of March was the orientation and intensity of the troughs and ridges. In this connection it may be pertinent to point out that fairly important transitions occurred within March.

During the first half of March, heights rose in the temperate latitudes of the mid-Pacific. Figure 3a shows this strong mean ridge and the two-trough Pacific pattern

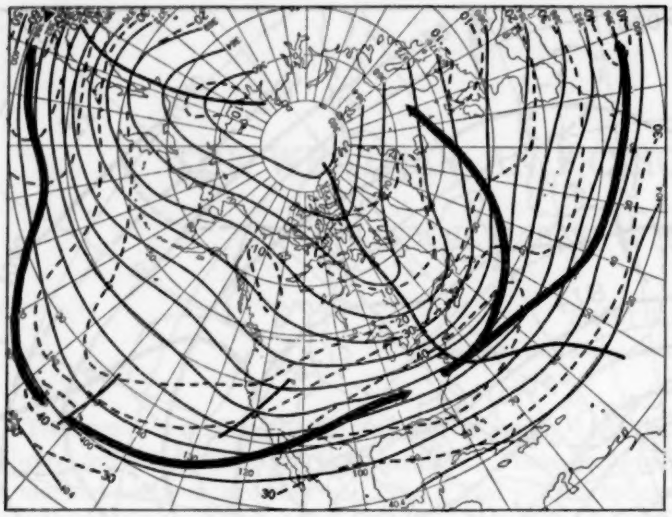


FIGURE 2.—Mean 200-mb. contours (in hundreds of feet) and geostrophic wind speeds (m./sec.) for the 30-day period March 2-31, 1954. A strong belt of lower-latitude westerly winds encircled a weaker westerly flow to the north in which the "sinusoidal" perturbations were embedded.

which accompanied it. This was a marked change from the strong cyclonic sweep at middle latitudes which dominated the whole ocean in February. Other changes of note included the association of the polar vortex with the Asiatic coastal trough rather than the North American trough. Related to this was the development of closed Low conditions near James Bay. This regime ended the prolonged spell of warm weather over most of the United States and brought frost or freezing temperatures as far south as the Florida Everglades and measurable amounts of snow all the way to the Gulf Coast (4 inches in parts of Mobile, Ala). On March 5 Cleveland, Ohio, reported five straight days of snow and wind with a total snowfall of 20.8 inches.

During the latter half of the month, a strong ridge, which began to build before the 15th, developed in the Gulf of Alaska (fig. 3b). The ridge was associated with a marked wave of blocking which retrograded very slowly across the eastern Pacific after a fairly rapid traverse of the blocking surge from the northeast Atlantic. The mean effect of this anomalous ridge (fig. 3b) was to produce northerly to northwesterly winds from the eastern Gulf of Alaska to Hudson Bay. Cold cP and mP air was swept southward into the north-central and northwestern United States in a broad confluence zone. Within this area repeated cyclogenesis gave rise to major storm developments which moved eastward as they deepened on the strong thermal contrast and were followed by cold air sweeps southward. (See tracks of cyclones and anticyclones, Charts IX and X.) The flat, fast, low latitude westerlies across the United States and Atlantic seem directly associated with this confluence pattern, and the former were a significant factor in the concomitant precipitation regime (Chart III).

A very similar blocking regime occurred in the Pacific during mid-January 1954 and has been described at length by Krueger [2]. For purposes of comparison, the mean

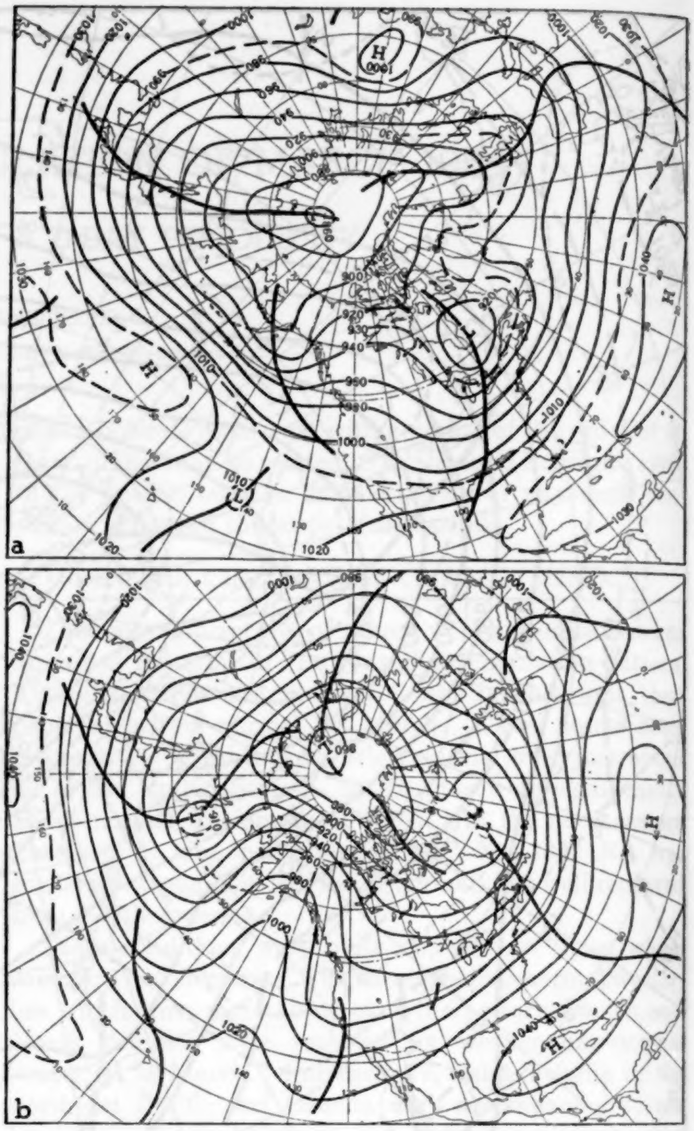


FIGURE 3.—(a) Fifteen-day mean 700-mb. heights for February 28-March 14, 1954. Strong subtropical ridge in central Pacific represented a marked change from the broad cyclonic sweep of February. Traces of blocking were evident in the North Atlantic. (b) Fifteen-day mean 700-mb. heights for March 17-31, 1954. Anticyclonic circulation dominated the northeast Pacific. Strong northwesterly flow over western Canada led to a broad zone of confluence over North America and marked intrusions of cold cP air into the United States.

heights for a 15-day mid-January period (9–23, inclusive) are shown in figure 4. The major characteristics of eastern Pacific ridge, west coast trough, and flat westerlies over the United States with a broad band of confluence over North America are notably similar. In general, the orientation, speed, and intensity of these transitions are strikingly alike.

SOUTHWESTERN DROUGHT

On March 1, 1954, the *Weekly Weather and Crop Bulletin* [7] reported "The moisture situation is critical in an area including extreme southwestern Nebraska, eastern sections of Colorado and New Mexico, and in western portions of Kansas, Oklahoma, and Texas, where frequent soil-drifting winds damaged small grains and pastures."

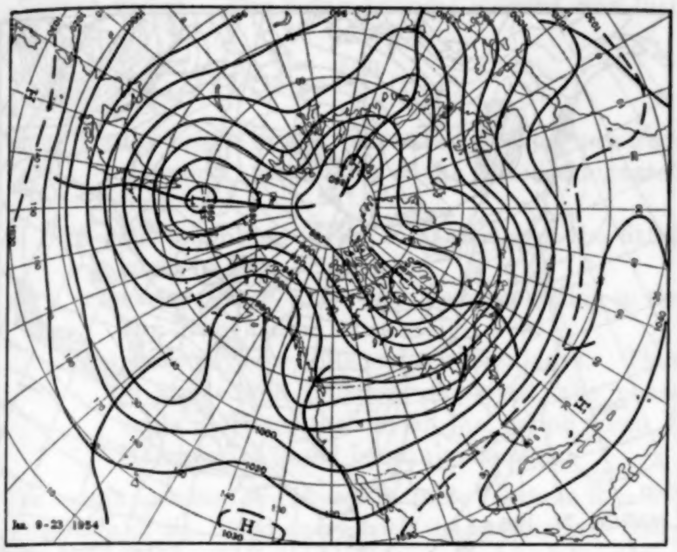


FIGURE 4.—Fifteen-day mean 700-mb. heights for January 9-23, 1954. Blocking in the eastern Pacific may be compared to that of latter half of March (fig. 3b). Speed of retrogression, intensity, and relation of even remote circulation features are quite similar.

During the first half of March this region was in the area of west-northwesterly flow with the mean trough located to its east in the Mississippi Valley (fig. 3a). Perturbations from the Pacific trough produced rain over the Far West and Northwest. Considerable amounts also occurred in and ahead of the Mississippi Valley trough. On the 10th and 11th (see fig. 5a for map of the 13th), a major cyclone spread considerable precipitation across the northern Plains. However, the major area of drought received no material alleviation.

In the latter half of the month (fig. 3b), fast westerlies at lower latitudes projected the rain shadow of the Rockies eastward over most of the drought area. Thus dry conditions prevailed in the generally confluent circulation pattern despite a broad mean trough in the western United States and cyclonic developments in the zone of cyclonic shear. Precipitation did affect all but southwestern Texas as these perturbations passed eastward. But no rains of consequence occurred in the outlined drought area due, in part at least, to the foehn desiccation of downslope westerly winds.

Much of this drought region had received less than 1.00 in. of precipitation in the last 4 months. Some localities were experiencing their worst drought on record, and Soil Conservation Officials placed the official title of "Dust Bowl" upon two areas, one in west Texas and New Mexico and the other in southeastern Colorado and southwestern Kansas. Total fields ruined by wind erosion extended over an area of some 12,000 square miles. Damage and crop losses were calculated in millions of dollars. Similarities to the winter-spring drought of 1903–04 were suggested. On that occasion, it is interesting to note, alleviation of the drought and initiation of a prolonged drought-free period occurred the following summer.

ANOTHER SPRING PERIODICITY

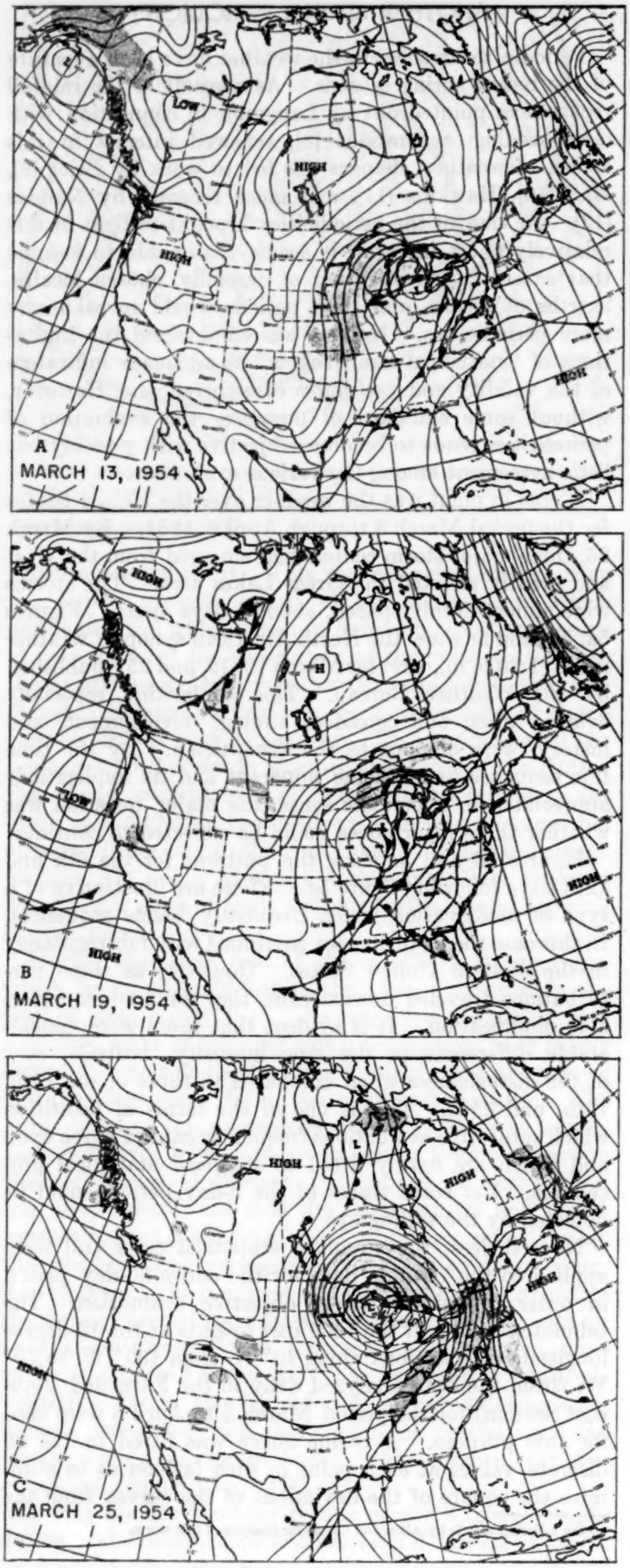
Periodic recurrences in the weather have been a feature of the recent spring seasons. As a result of the rainfall recurrences pointed out by Langmuir in connection with cloud-seeding evaluations [8], renewed interest in this aspect of weather changes has led to work by Brier [9], Hall [10], Hawkins [11], and more recently by Namias [12]. In view of the periodicities brought to light in this relatively short interval, it seems reasonable to assume that extensive investigation of carefully chosen locales, lengths of record, and time periods would reveal many more periodicities. Namias has emphasized the limitations of "statistical straitjackets" as adequate indicators of the validity and usefulness of recurrences. However, without some standard of measure, the evaluation of periodicities tends to become subjective with possibly but little agreement among the various evaluators.

A case in point was the weather over the United States for the period March 8 through April 6, 1954. By March 25, three major storm centers had emerged from the West and greatly affected the Great Lakes area. The storms were almost evenly spaced, about 6 days apart. Figures 5a, 5b, and 5c show the North American synoptic weather maps (1:30 p. m., EST) for March 13, 19, and 25,[2] published by the Weather Bureau. The similarities, especially evident when one considers timing, development, and history, were obvious to the synoptician. By the time this sequence had become apparent and its implications appreciated in a periodic sense, the major question was whether these recurrences could be expected to continue.

Figures 5d and 5e show the patterns for the 6th and 12th days following figure 5c. These are illustrative of a type of modification which frequently besets sequences. In this case the disturbances continued with fair regularity in the western United States. However, as these perturbations traveled downstream, they suffered considerable modification. It is evident that there were considerable differences in the size, intensity, latitude, etc., of the disturbances when compared to those of the 13th, 19th, and 25th. This is one of the forms of transition which subjective evaluations frequently cannot agree upon and which are hardly fitted to standard statistical procedures. Yet some traces of the 6-day period could be detected by the willing eye.

Nevertheless, the standard statistical tests [13] were applied to the 700-mb. data for the entire 30-day period in order to gain a purely objective evaluation. The tabulated values of the 1500 GMT heights at the 10-degree longitude intersections along 40° N. from 130° W. to 70° W. (from the data analyzed daily in the Extended Forecast Section) for the period March 8 to April 6 were used for this purpose. A cosine curve was fitted to the 30 discrete values at each point in such fashion as to minimize the square of the deviations of the curves from the

[2] See adjacent article by Allen and Creasi for analysis of this storm.



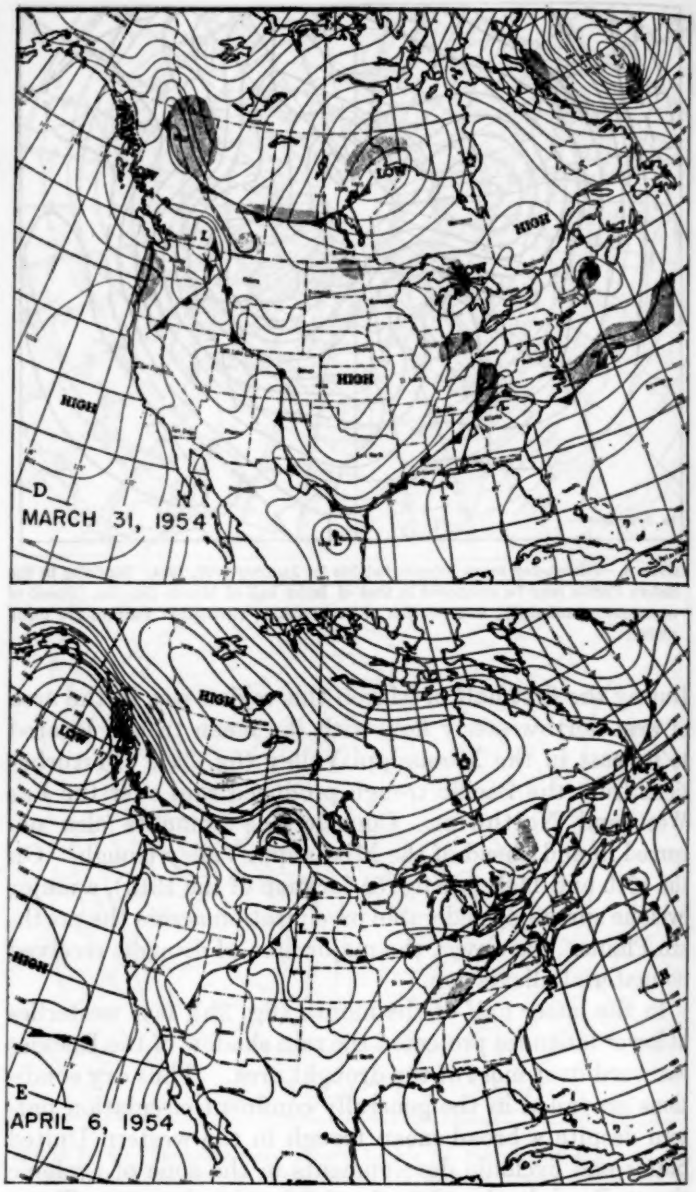


FIGURE 5.—Synoptic sea level maps 6 days apart. Note marked resemblance of disturbances in the Great Lakes region on (A), (B), and (C). These storms were major weather producers with similar histories and showed obvious periodicity. Maps in (D) and (E) show deterioration of the recurrence in the Great Lakes area, although traces of the periodicity seemed to persist.

observed values. The 6-day periodic element was then expressed

$$Y = A \cos \frac{360}{6} (x - \theta)$$

where Y = the height in feet (expressed as departure from the mean) for the day of the period designated by x.

A = the amplitude (½ the total swing) of the fitted curve in feet.

x varies from 0, 1, 2, . . . 5 corresponding to the day in the period.

θ = phase angle in units and tenths of days. Thus in the cosine function employed, the phase angle indicates the day in the period when Y (the height) would be at a maximum.

The results obtained are shown in table 1, where R is the correlation of the fitted curve with the appropriate daily height values for all of the 30 days.

TABLE 1.—*Amplitude, phase angle, and correlation of the 6-day periodic component in the 700-mb. heights along 40° N. lat., March 8 to April 6, 1954.*

Element	Longitude (° W.)						
	130	120	110	100	90	80	70
Amplitude (ft.)	104	188	199	194	130	168	199
Phase angle (days)	5.1	0.0	0.5	1.1	2.6	3.8	4.5
R	.27	.54	.60	.50	.39	.48	.47

It is evident that a periodicity of appreciable proportions was manifest during this 30-day interval even by rigid statistical standards. The closest approximation to simple sinusoidal oscillation was at 40° N., 110° W., where a 6-day cosine wave with amplitude of about 200 ft. accounts for more than ⅓ of the variability which occurred there between March 8 and April 6. A like test of sea level pressures at Salt Lake City showed an amplitude of 8.2 mb. with a correlation of 0.72 for a similarly fitted 6-day wave. It is quite likely that the general level of the correlations could be raised by omitting the last 6 days.

A further test of the cycle lies in the progression of the phase angle with longitude. If the perturbations travel downstream, a regular or at least consistent variation of phase with latitude should be evident. Table 1 shows such a progression. For instance, the maximum (or minimum) of the periodic component of the height changes occurred 1.1 days (1.1−0.0) later at 100° W. than it did at 120° W. It took 2.7 days (3.8−1.1) to travel from 100° W. to 80° W. Thus, although the speed of eastward motion is not constant, there is a real progression eastward in the desired physical sense.

In relation to previous periodicities reported, several statements can be made:

1. This was a fairly strong, well-marked recurrence, although the effect did not seem to persist as long as the more prominent previous recurrences [8, 9, 12].
2. It reached its maximum of amplitude and correlation roughly in the area of strong cyclonic curvature aloft if one uses figure 3b as indicative of mean conditions. This agrees with the association suggested by Namias [12].
3. No relationship has yet been established between mean circulation and the time between recurrences. This relationship can possibly be established by the further accumulation and processing of data.
4. Reports in the past have shown that cloud seeding is generally practiced when the meteorological situation is favorable for rain. If pulses arrive periodically from the Pacific, then seeding is usually timed to meet these events. A critical test of the effects of cloud seeding on the production or control of periodicities is quite difficult under these circumstances.

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CHANGES IN THE VERTICAL MASS DISTRIBUTION IN THE VICINITY OF THE RAPIDLY DEEPENING LOW OF MARCH 24-26, 1954

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INTRODUCTION

Weather forecasters frequently miss sudden changes in the intensity of Lows and Highs, and even more frequently miss rapid changes of pressure not associated with the centers of systems. The complex combination of circumstances which results in pressure change is only partially understood in the best of situations, and most forecasters still rely heavily on simple extrapolation of the past movement and intensity of systems and their changes for the construction of prognostic pressure fields. Attempts to forecast major changes in these properties, while frequently successful, have rarely been based on complete understanding of the processes involved. A case history such as this cannot possibly close the gaps in the basic understanding of pressure changes, but it will attempt to record for whatever purpose it may be useful, the change in mass, at least, about a rapidly deepening Low, and to deduce therefrom an instructive, though admittedly incomplete, explanation of the deepening.

BACKGROUND

Explanations of large pressure changes, including the change of intensity of systems, fall generally in two categories. What Austin [1, 2] calls the thermal theory attributes the change of pressure to the change of density in the air column over the point of measurement. Density being inversely proportional to the temperature, warming or cooling within this air column will, according to this theory, produce falling or rising pressures, respectively, at the base of the column. Theoretical support for this is found in the hydrostatic equation. The mechanisms by which such temperature changes may occur are many, but the one considered most capable of rapidly producing large changes in the troposphere is the advection process by which air masses or layers having different temperatures are moved through the sides of the column by the existing wind. Other temperature changes are possible as a result of adiabatic processes of lifting or sinking, or by nonadiabatic processes such as radiational cooling in cold anticyclones and surface heating in warm or thermal Lows. The release of latent heat also affects the density and may be a source of pressure change. It is generally agreed, however, that these latter processes normally result in relatively small changes, and that advection, alone of the thermal processes, can be responsible for large changes. This approach leaves unanswered, questions as to the source of warm or cold air, what initiates the advection, and why the particular wind fields develop. If thermal theories provide adequate explanation of barotropic pressure changes in the troposphere, the cause of the changes must frequently be found in the upper stratosphere, or less than one-fifth of the atmosphere where the data are insufficient to provide decisive answers.

A second approach is based on the accumulation and depletion of air due to the wind field and may be called the dynamic approach. Pressure variations are considered in this case to be due to convergent or divergent flow, or to the vorticity of the upper flow. These produce changes in the mass of vertical air columns by differences between the inflow and outflow of the columns, resulting in either adiabatic changes in temperature or changes in the vertical extent of the atmosphere, or both. Bjerknes [3] explains the pressure falls ahead of a cyclone by the excess of divergence aloft over convergence near the surface, and the rises to the rear by the reverse distribution. Deepening of a Low would then occur when, over the surface center, the balance between the two processes became tipped in favor of the divergence. The Bjerknes model permits, but does not require, aid from the advection and other thermal processes. Several rules have evolved for predicting the deepening and filling of systems, based on the shape of the upper level streamlines.[1] Application of the various theories comprising the dynamic approach frequently runs into difficulties due to the wide separation of reporting stations and the inaccuracies of wind measurements.

Of these approaches, the advection concept is the one now most frequently used by forecasters, largely because

[1] Schmidt [4] has summarized some of these rules as follows;
a. If the high level isobars diverge uniformly (i. e., the distribution of gradient across stream remains the same, changing only in strength and/or direction along the stream), surface pressure falls (rises) if the largest gradients lie on the high- (low-) pressure side.
b. If the high-level isobars converge uniformly, surface pressure rises (falls) if the largest gradients lie on the high- (low-) pressure side.

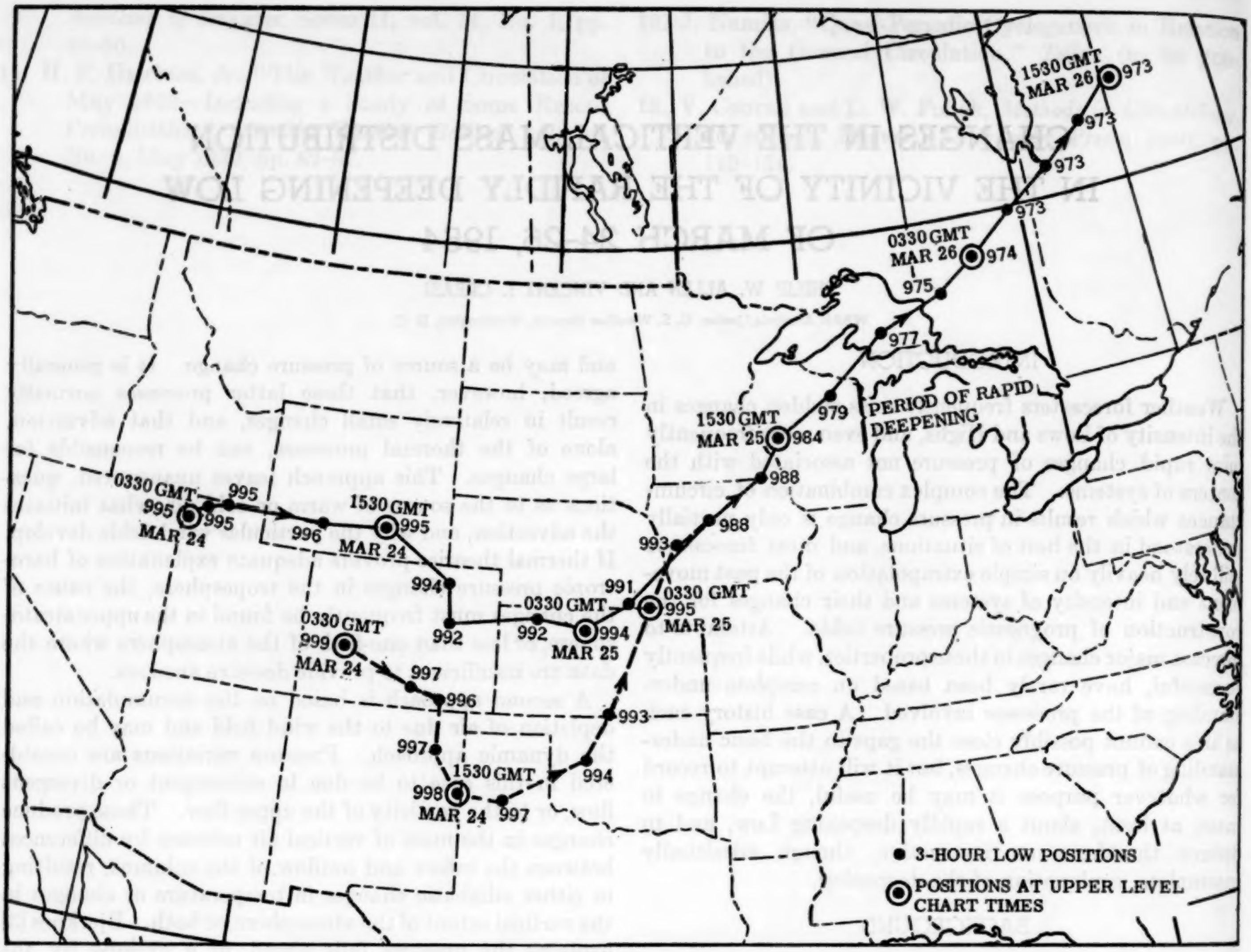

FIGURE 1.—The sea level track and central pressures of the deepening Low of March 24–26, 1954.

the thermal pattern is more easily derived and represented than are convergence-divergence or vorticity patterns. However, the use of vorticity patterns has increased in recent years. Fjørtoft[5] has developed a technique which may be used in the average forecasting center, for deriving graphically a "space mean" or smoothed flow pattern, with isopleths of vorticity as the difference between the smoothed flow and the actual flow, and he suggests a way of constructing prognostic upper air charts by moving the centers of vorticity along the mean flow, then subtracting the new vorticity from the mean flow to get the prognostic contours.

Vederman[6] studied the changes in mass between the standard raob levels over the centers of 25 rapidly deepening Lows, showing that the greatest depletion of mass in this type of system normally appears above the 200-mb. surface. The method employed by Vederman has been used in the current study, and extended to show the changes in mass out to about 350 miles from the center.

DEVELOPMENTS PRIOR TO DEEPENING

The Low of March 24–26, 1954, was selected for study because of its rapid deepening—20 mb. in 24 hours and 9 mb. in a 6-hour period (fig. 1)—and because its development apparently contributed toward a polar outbreak which spread record-breaking low temperatures into the North Central States. Its early history was quite similar to that of a Low which occurred only a week earlier but which did not deepen. Both Lows formed with about the same depth over Nevada and in association with the eastward drift of pockets of cold air which had become cut off from the polar cold source. Both moved eastward with little change of intensity as far as Kansas, but differences appeared in the surrounding atmosphere to change the subsequent course and development of the second Low. A blocking action which had just begun to be effective over northwestern Canada with the earlier cold pocket became much more pronounced and had retro-

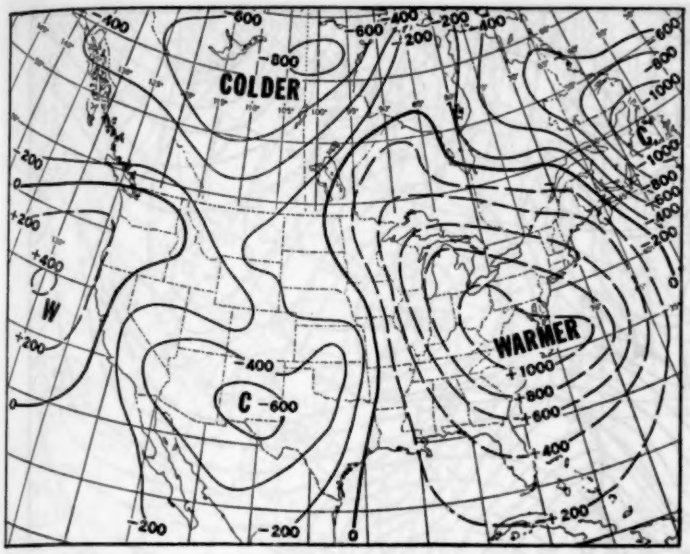

FIGURE 2.—The total change of thickness between the 1,000- and 500-mb. surfaces during the 3-day period March 22-25, 1954, showing the strong warming which occurred over eastern United States preceding cyclogenesis.

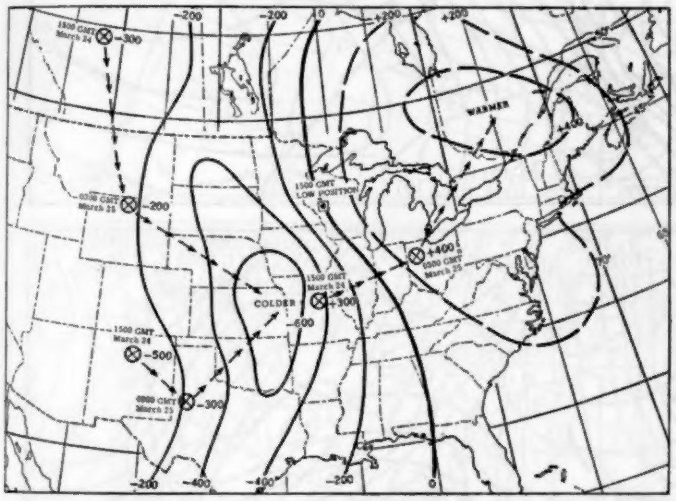

FIGURE 3.—The 12-hour thickness change during the first part of the period of deepening, and the past positions of the change centers, showing juncture of cold advection centers.

gressed westward to the eastern Pacific by the time of the second cutoff cold pool. The eastern United States was flooded with cold air prior to the first Low, but 3 days of strong warming (fig. 2) preceded the second, so that while the earlier Low was carried generally eastward from northern Nevada to New York, reaching a minimum central pressure of 988 mb. over Kansas and filling for 12 hours thereafter, the later one took a more northerly course around the warm air and deepened rapidly, as indicated in figure 1. The southern (dashed) track in this figure belongs to a secondary pressure minimum which preceded the main Low across the Plateau and attached itself to the polar front which lay across central Texas. A frontal wave formed (fig. 4), the warm sector of which contained the warmest air thus far of the spring season.

Meanwhile, the cold pocket had moved inland to the Plateau region, accompanied by a weak short-wave upper trough, figure 5. The long-wave trough remained just west of the California coast, where it was re-deepened by a new surge of cold air from the north. The newest cold outbreak also provided the energy necessary to displace the Arctic front southward from its quasi-stationary position through Montana and southern Manitoba. Figure 3 shows, by means of the 12-hour thickness change between the 1000- and 500-mb. surfaces, the progress of the Arctic air along the east side of the Continental Divide. The momentum of this air, extending up to 500 mb. as evidenced by the increased northwesterly flow bridging over the Pacific coast trough, was added to that of the cold air mass from the Plateau to displace a large amount of warm air from the Western Plains between 0300 GMT and 1500 GMT on the 25th. An unusually strong solenoidal field was produced across Kansas and Nebraska with the proximity of Arctic and tropical air masses, so that the superposition of the cyclonic vorticity of the upper level trough completed the conditions customarily considered necessary for strong cyclogenesis.

Significant deepening had not been predicted until early on the 25th, but the Prognostic Discussion issued by the WBAN Analysis Center with the prognostic chart based on the 0630 GMT data read in part: "The outstanding feature of the surface chart is the deep low over central United States. The advection of warm air and vorticity and Palmer's objective technique [7] indicate rapid northeastward motion of this storm. Marked deepening of this storm is expected as it moves under much lower heights aloft."

DEVELOPMENTS DURING AND FOLLOWING DEEPENING

Deepening occurred in steps, the central pressure falling from 994 mb. at 0330 GMT on the 25th to 988 mb. 6 hours later, leveling, then plunging 9 mb. in 6 more hours to 979 mb. at 1830 GMT. The 1500 GMT raobs were taken in the middle of the period of most rapid deepening. The height of the closed circulation did not change appreciably from just under 300 mb. during the deepening process, although the number of closed sea level isobars increased by nine (27 mb.).

The wave on the polar front developed rapidly, with severe thunderstorms and a few tornadoes occurring along the cold front from the Texas Panhandle to eastern Kansas on the 24th and thence through Missouri and Illinois on the 25th as the wave occluded. Maximum vertical instability occurred near the point of occlusion, although some squall activity moved out along the warm front. Heavy rainfall amounting in some localities to over 4 inches spread in a relatively narrow band across northern Missouri, southeastern Iowa, northern Illinois, Indiana, and Ohio, and southern Michigan. Some of the areas affected had previously been in serious drought. The rain just missed other areas which continued dry.

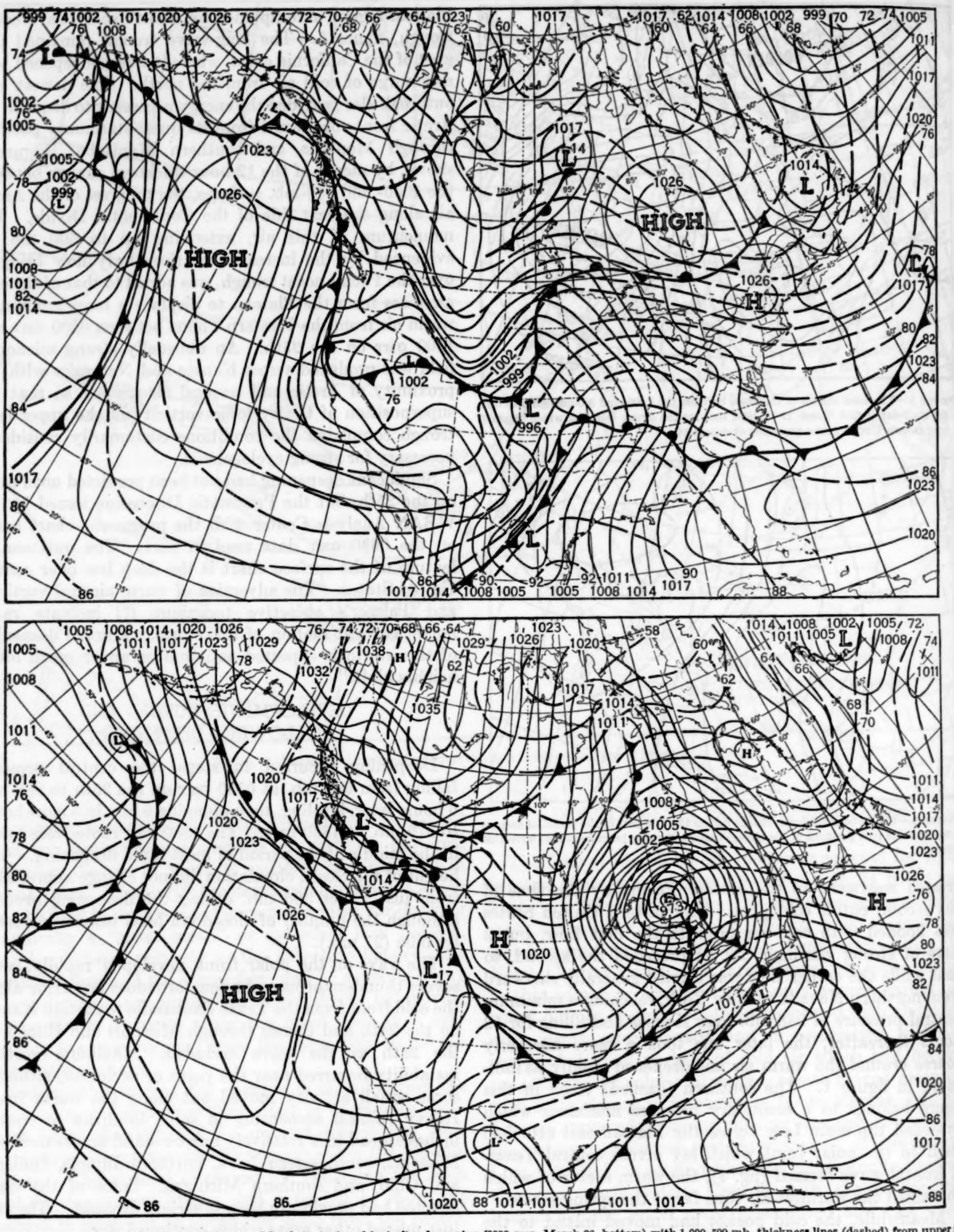

FIGURE 4.—Sea level charts just before (0030 GMT, March 25, top) and just after deepening (0030 GMT, March 26, bottom) with 1,000–500-mb. thickness lines (dashed) from upper air data 3 hours later, showing the near approach of Arctic and tropical air masses, strengthening thermal gradient, and subsequent deepening.

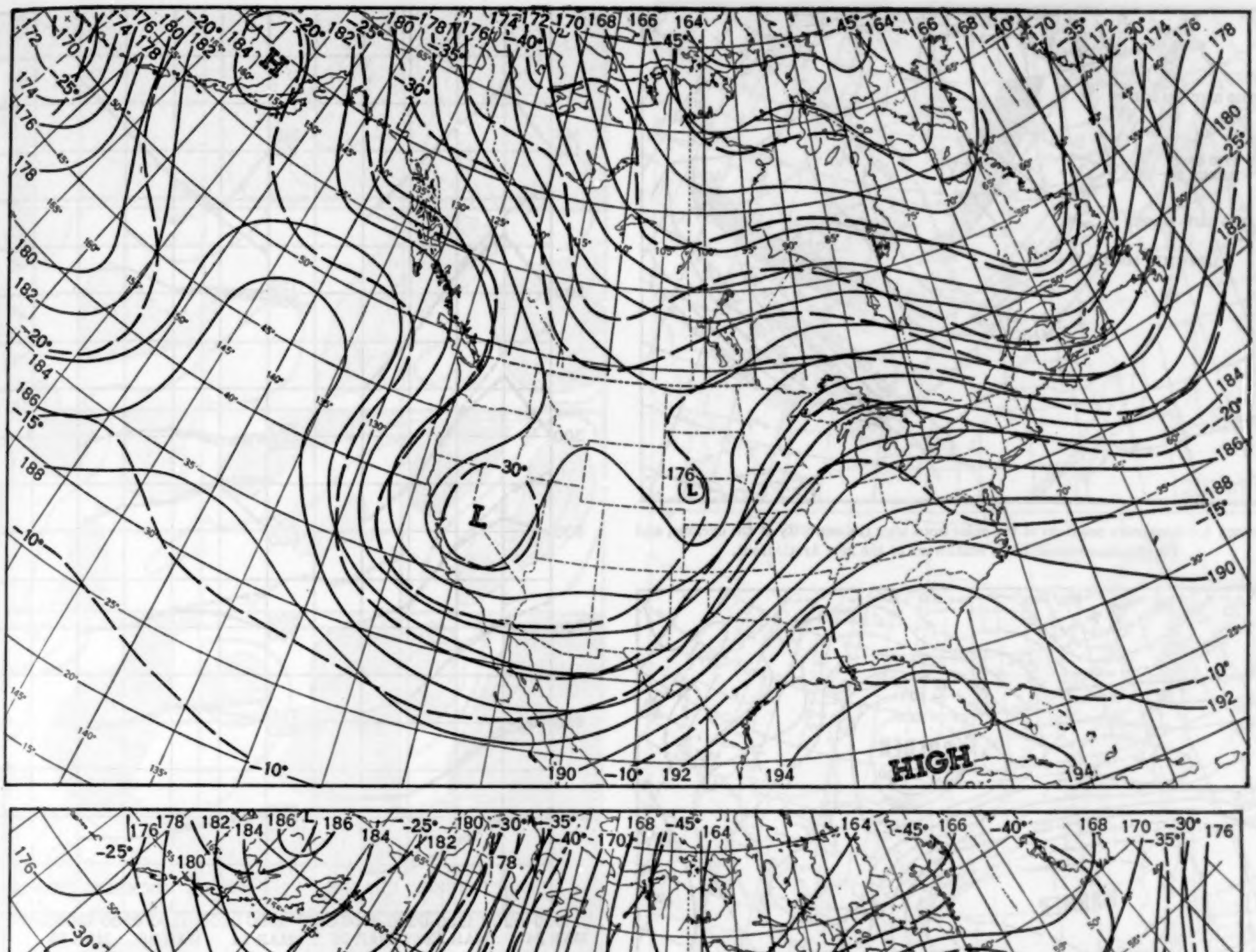

FIGURE 5.—500-mb. contours and isotherms (dashed) just before (0300 GMT, March 25, top) and just after deepening (0300 GMT, March 26, bottom). Note the blocking ridge in the eastern Pacific and the cold Low over California.

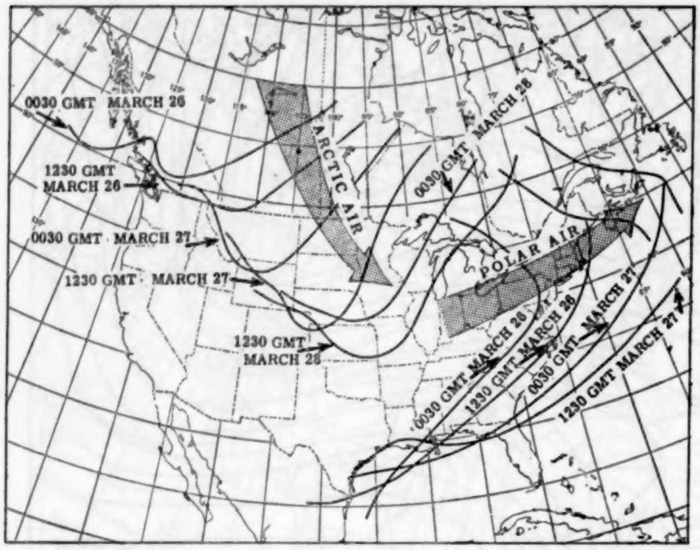

FIGURE 6.—Successive positions of the polar front after the maturity of the cyclone, and the simultaneous advance southward of the new Arctic front.

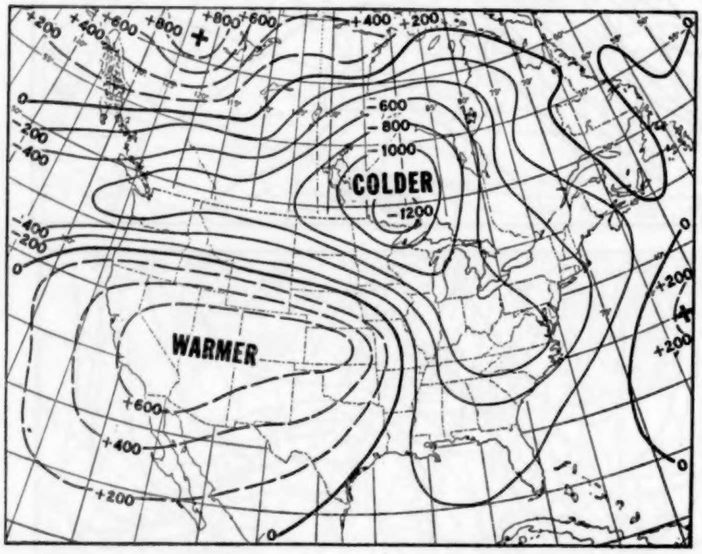

FIGURE 7.—The total change of thickness between the 1,000- and 500-mb. surfaces during the 3-day period March 25-28, 1954, showing the strong cooling which followed the cyclone.

The surface center continued to move northeastward, coming under the closed upper Low which had been in the Hudson Bay region for several days. The cyclonic circulation in the lower troposphere over this area was thus markedly strengthened, and the resulting northerly current over western Canada was in a large measure responsible, together with the persistence of the blocking ridge in the eastern Pacific, for the southward transport of the abnormally cold air mass (fig. 6) which had been forming over the Yukon Territory and Alaska. Although some of it moved southwestward into the Pacific, a large portion of this cold air spread southeastward into northern and eastern United States (fig. 7). Minimum temperature records for the date were established in northern Minnesota, International Falls recording $-5°$ F. on the 28th, $-5°$ F. on the 29th, and $-11°$ F. on the 30th.

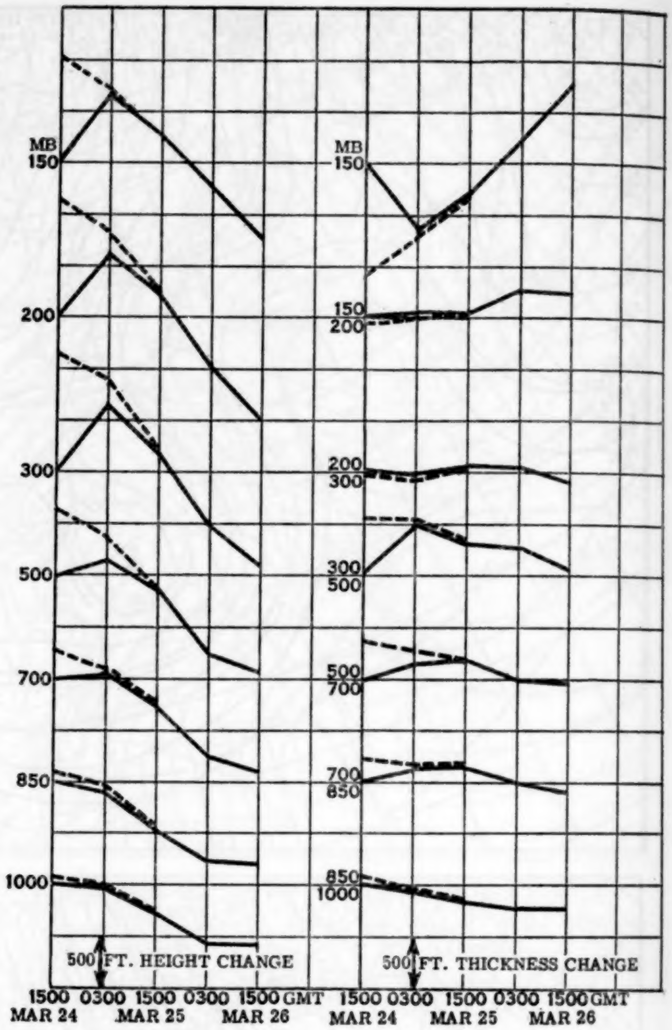

FIGURE 8.—Changes in the heigths (left) and thicknesses (right) at and between standard pressure surfaces directly over the sea level low center. The solid lines refer to the original Low, the dashed lines to the wave on the polar front prior to their merger.

DISCUSSION OF MASS CHANGES

Graphical subtraction of successive levels of carefully reanalyzed constant pressure charts produced thickness isopleths for all layers up to 150 mb. for the three raob times representing the period of rapid deepening. The changes in thickness over the moving Low center were determined for the two 12-hour periods and the overall 24-hour period of deepening, and are shown in figure 8. These agree well with Vederman's results. The thickness charts were subtracted graphically to get the 12-hour and 24-hour change over the area around the surface Low (fig. 9). This was done with the surface Low positions superimposed so that the coordinates of the changes are related to the Low rather than to the surface over which it was moving. The direction of motion of the Low was not far from 45° east of north through the period. The top squares in figure 9 and the top right graph in figure 8 are the height changes of the 150-mb. surface with the sign reversed. These might be interpreted as the

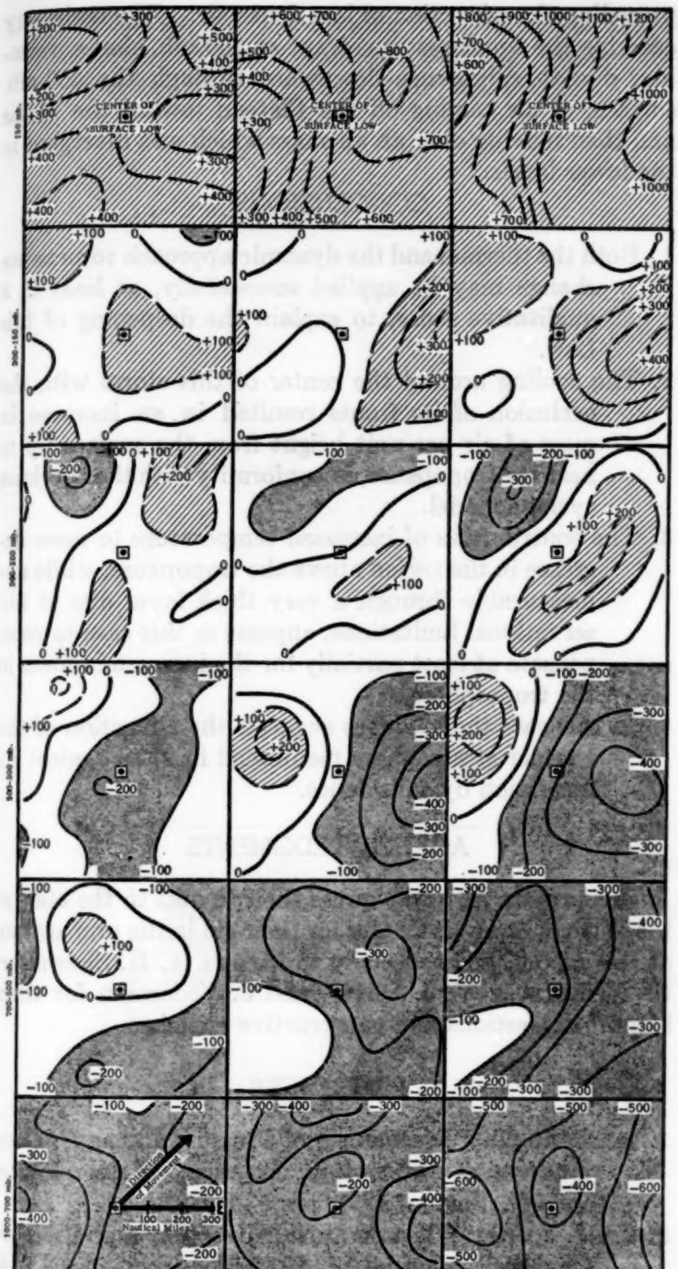

FIGURE 9.—Changes in the thickness between indicated mandatory pressure surfaces, computed relative to the moving sea level Low center, showing the distribution of warming and cooling in the vicinity of the lowest pressure.

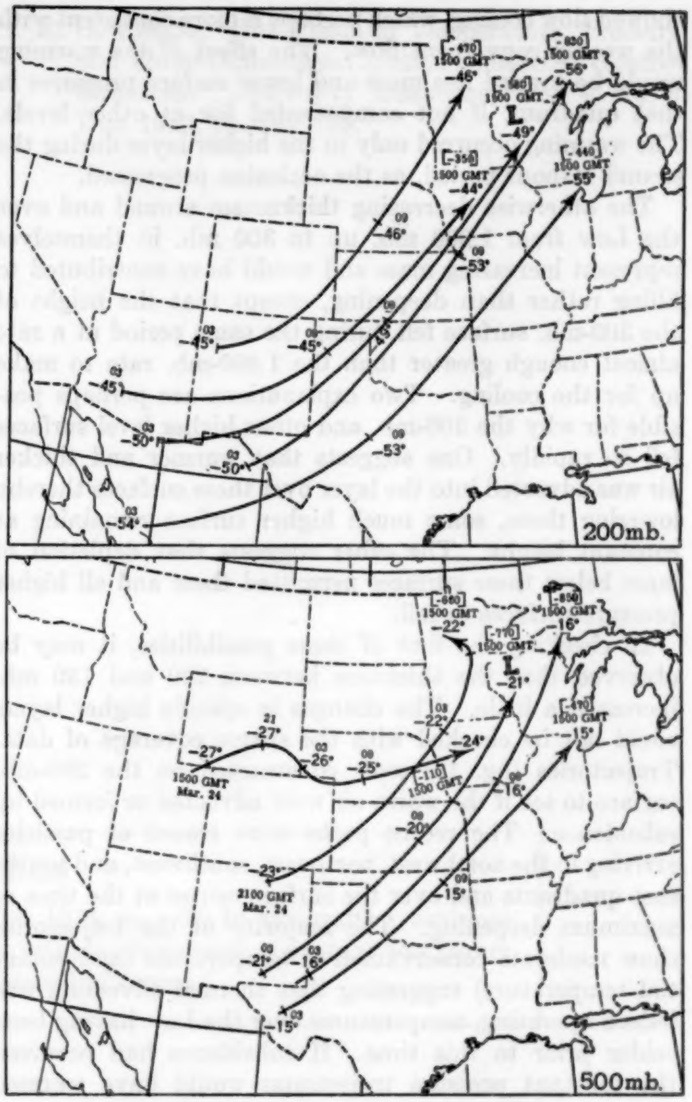

FIGURE 10.—Trajectories of air particles into the vicinity of the Low, showing differences in source, speed, and temperature of air arriving over the Low at time of rapid deepening. 12-hour changes in trajectory altitude (ft.) are shown in brackets.

thickness changes between the 150-mb. surface and some very high fixed surface near the top of the atmosphere.

These charts show general cooling relative to the Low below the 700-mb. surface within at least 350 miles of the center throughout the period of deepening, although individual stations in advance of the Low reported warming. This is in agreement with our concept of the occlusion process, in which cold air surrounds the Low in the lower levels, the warm air being lifted and the cold air becoming deeper with time. Fleagle [8] in similar cases attributes at least part of the cooling in the lower levels to upward motion. The strong cooling observed to the east of the Low up to 300 mb. in the second period was almost certainly due to upward motion from the convergent lower levels to the divergent flow near the tropopause, which was near 200 mb. in that quadrant. The strong warming above the 200-mb. surface in the northeast quadrant was probably advected, as shown hereafter, rather than adiabatic warming of air descending to the level of maximum divergence. Note that, relative to the Low, the advection of cold air in the southwest quadrant was not greater than the cooling in other quadrants during the second period, although individual stations in that area were the ones to feel the influx of cold air behind the cold front. Warming from 700 to 300 mb. continued in the northwest quadrant of the Low as it moved under a relatively stagnant pool of warm air over the Dakotas (see fig. 5 and the 500-mb. chart for 0300 GMT on the 25th). Individual stations in this pool

showed slow cooling, which perhaps is more consistent with the weakly convergent flow. The effect of the warming would be toward less mass and lower surface pressures in that quadrant, if not compensated for at other levels. The warming occurred only in the higher layer during the second 12-hour period, as the occlusion progressed.

The otherwise decreasing thicknesses around and over the Low from 1,000 mb. up to 300 mb. in themselves represent increasing mass and would have contributed to filling rather than deepening, except that the height of the 300-mb. surface fell during the same period at a rate almost enough greater than the 1,000-mb. rate to make up for the cooling. Two explanations are perhaps possible for why the 300-mb. and other higher level surfaces fell so rapidly. One suggests that warmer and thicker air was advected into the layer over these surfaces thereby lowering them, some much higher surface remaining at constant height. The other suggests that depletion of mass below these surfaces permitted them and all higher pressure surfaces to fall.

In checking the first of these possibilities, it may be observed that the thickness between 200 and 150 mb. increased a little. The changes in specific higher layers could not be checked with the sparse coverage of data. Trajectories (fig. 10) were constructed on the 200-mb. surface to see if the warm air were advected or formed by subsidence. The recent paths were traced of particles arriving in the northwest, northeast, southwest, and southeast quadrants and over the surface center at the time of maximum deepening. The majority of the trajectories show moderate conservatism of temperature (and potential temperature) suggesting that thermal advection was indeed operating, temperatures over the Low having been colder prior to this time. If subsidence had occurred the constant pressure trajectories would have warmed with time. However, this warmer air did move downslope in coming over the Low, the amount of height change in 12 hours of trajectory being indicated in brackets at the trajectory endpoints. The 200-mb. trajectory fall was about equal to the fall in height of that surface over the Low center for the same period, so that it appears that whether or not the advection produced the sinking of the isobaric surfaces, it was at least associated with it. The presence of divergence ahead of the Low having already been indicated, we must assume that in this case both processes were involved in the deepening. Trajectories were constructed also on the 500-mb. surface to show differences in the transport at that level. The same conservatism of temperature was evident at the lower level.

It may be instructive to consider the trajectories of figure 10 from other aspects. The one entering the northeast quadrant of the Low at 200 mb. is interesting in that it shows cooling. This may have been a result of some upward motion through the 200-mb. surface, perhaps associated with the divergence aloft in that quadrant and preceding the advection of less dense air. The trajectory entering the southwest quadrant at 500 mb. shows warming, due to subsidence downward through the 500-mb. surface, of air coming off the Plateau toward the Plains and then moving over an air mass which was divergent in the lower levels.

CONCLUSIONS

1. Both the thermal and the dynamic approach to pressure change may be applied successfully, at least in a qualitative sense, to explain the deepening of this Low.
2. The cooling around the center of this storm with the occlusion of its fronts resulted in an increase in mass of air per unit height from the surface up to near the tropopause, in conformity with the Bjerknes cyclone model.
3. The contribution of increased temperature to mass decrease in the region above the tropopause, while not measurable through a very thick layer due to observational limitations, appears in this case to compensate at least partially for the increase in mass in the troposphere.
4. In this case the evidence suggests the advection of the warmer stratosphere mentioned in 2, as against its formation by subsidence.

ACKNOWLEDGMENTS

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CORRECTION

MONTHLY WEATHER REVIEW, vol. 82, No. 2, Feb. 1954, page 60: In paragraph 1, sentence 3 should read, "For the country as a whole the weighted temperature average was higher than for any *previous* February in the *62-year* period of record."

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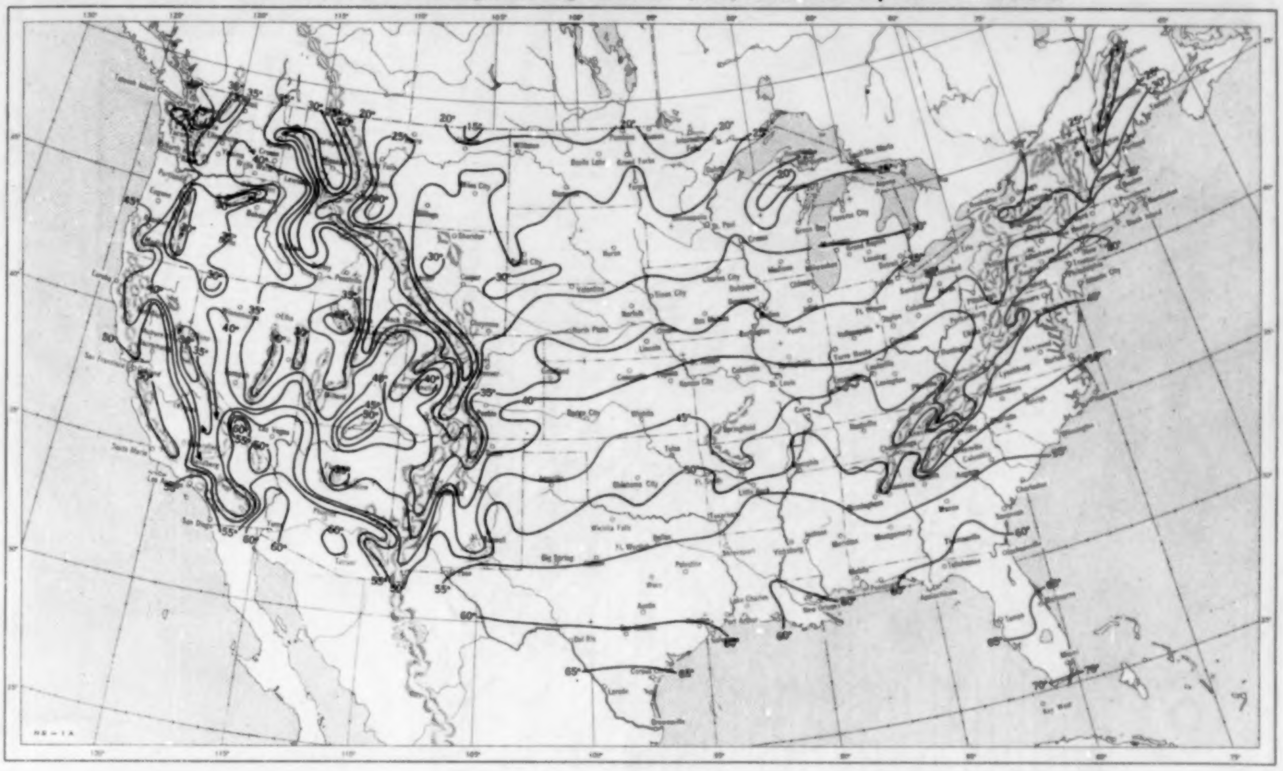
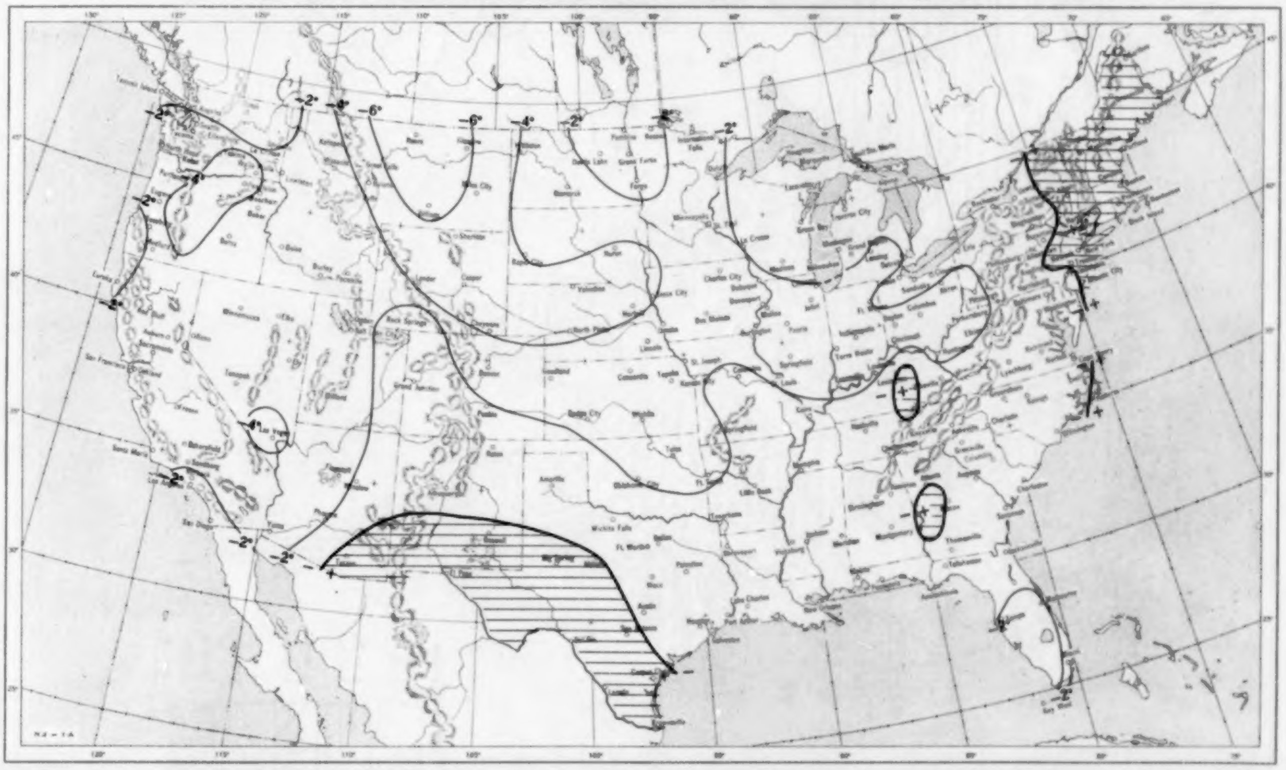
Chart I. A. Average Temperature (°F.) at Surface, March 1954.

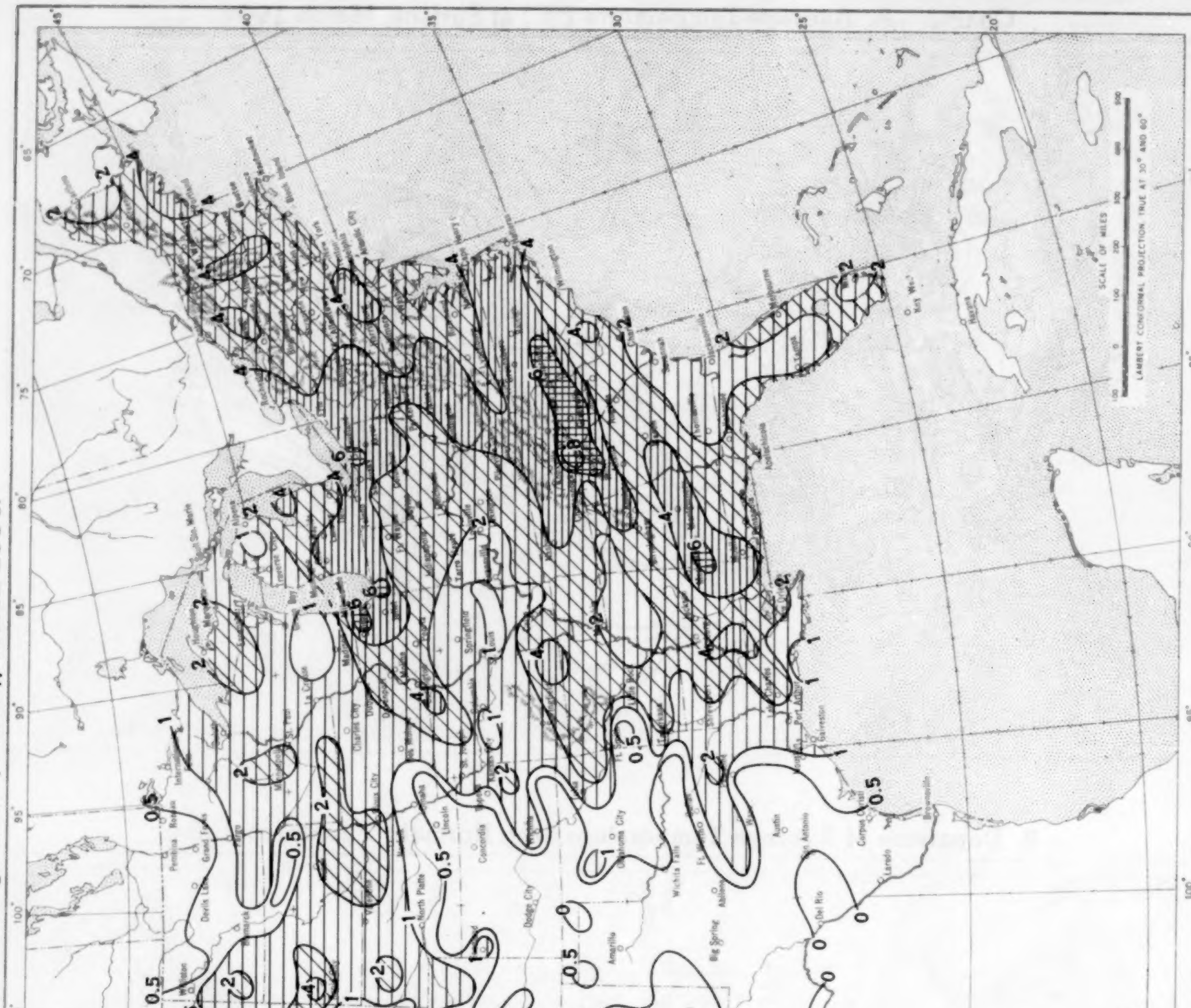


B. Departure of Average Temperature from Normal (°F.), March 1954.



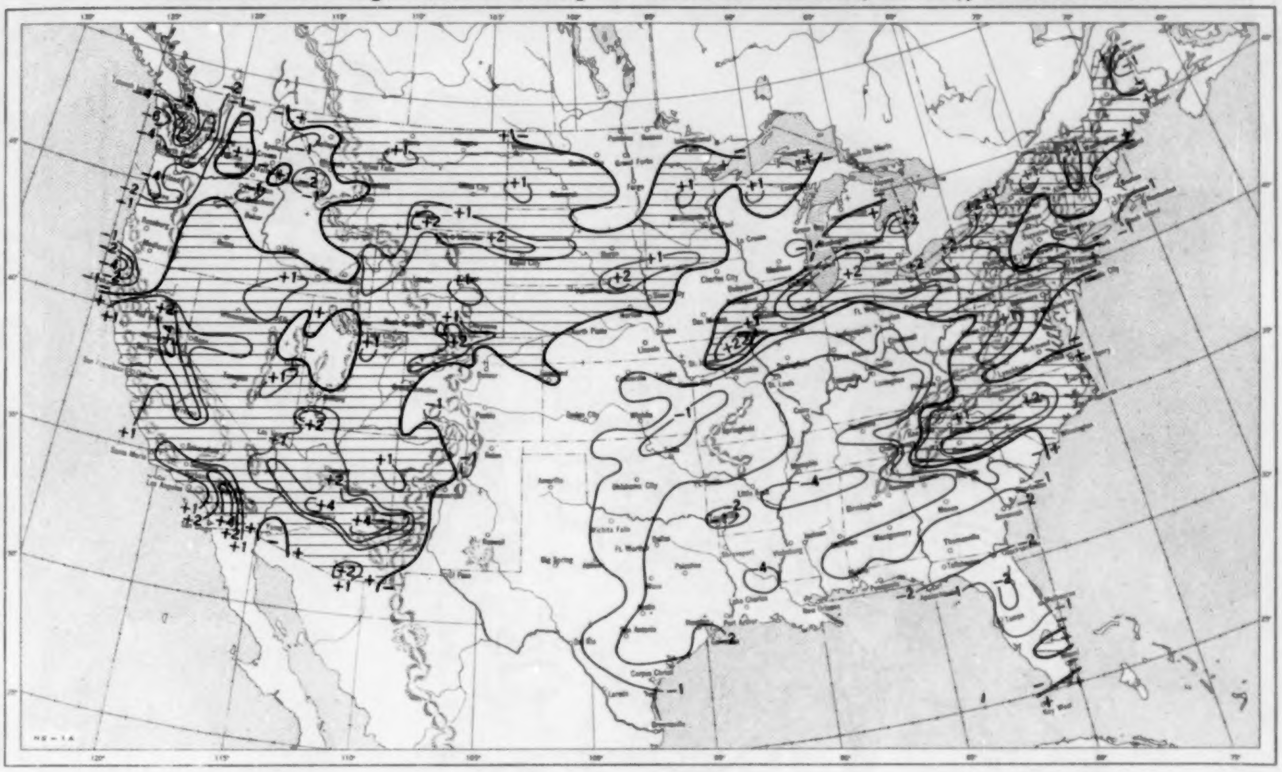
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), March 1954.

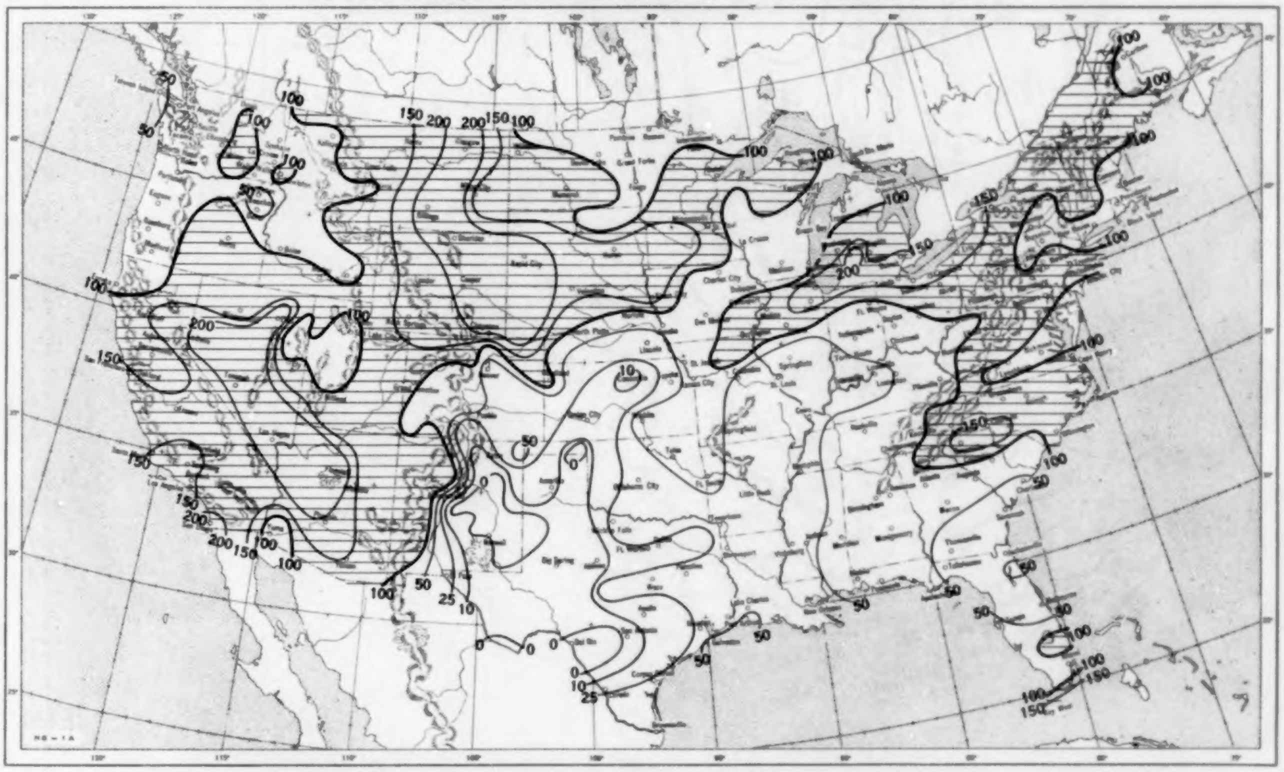


Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), March 1954.

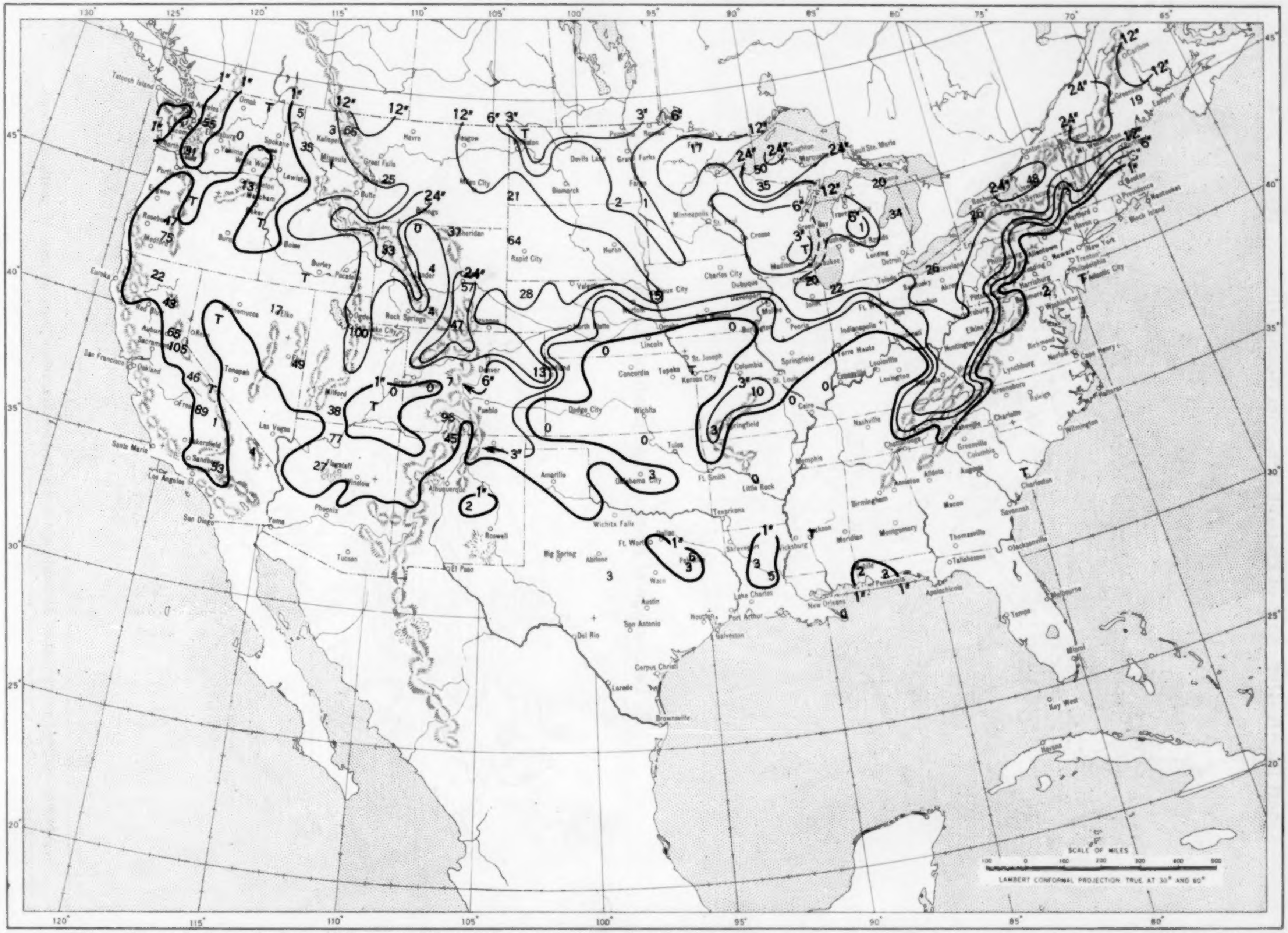


B. Percentage of Normal Precipitation, March 1954.



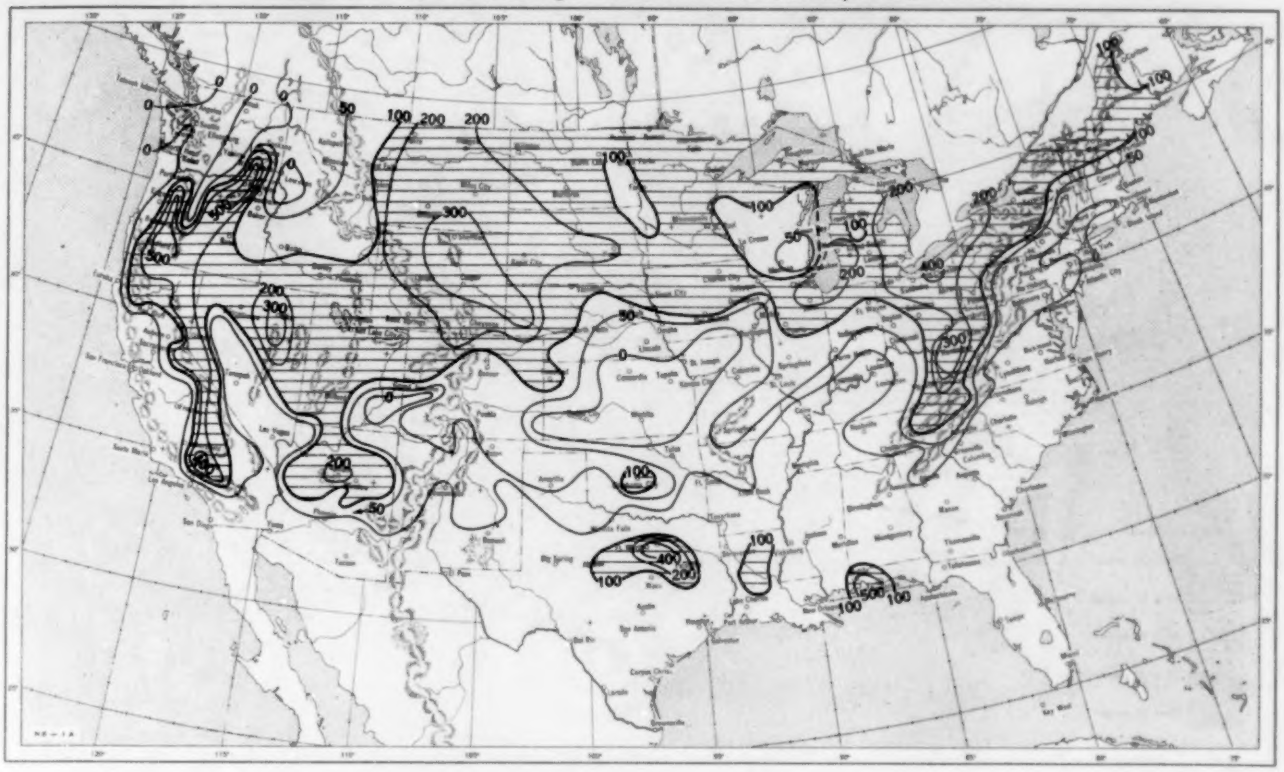
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), March 1954.

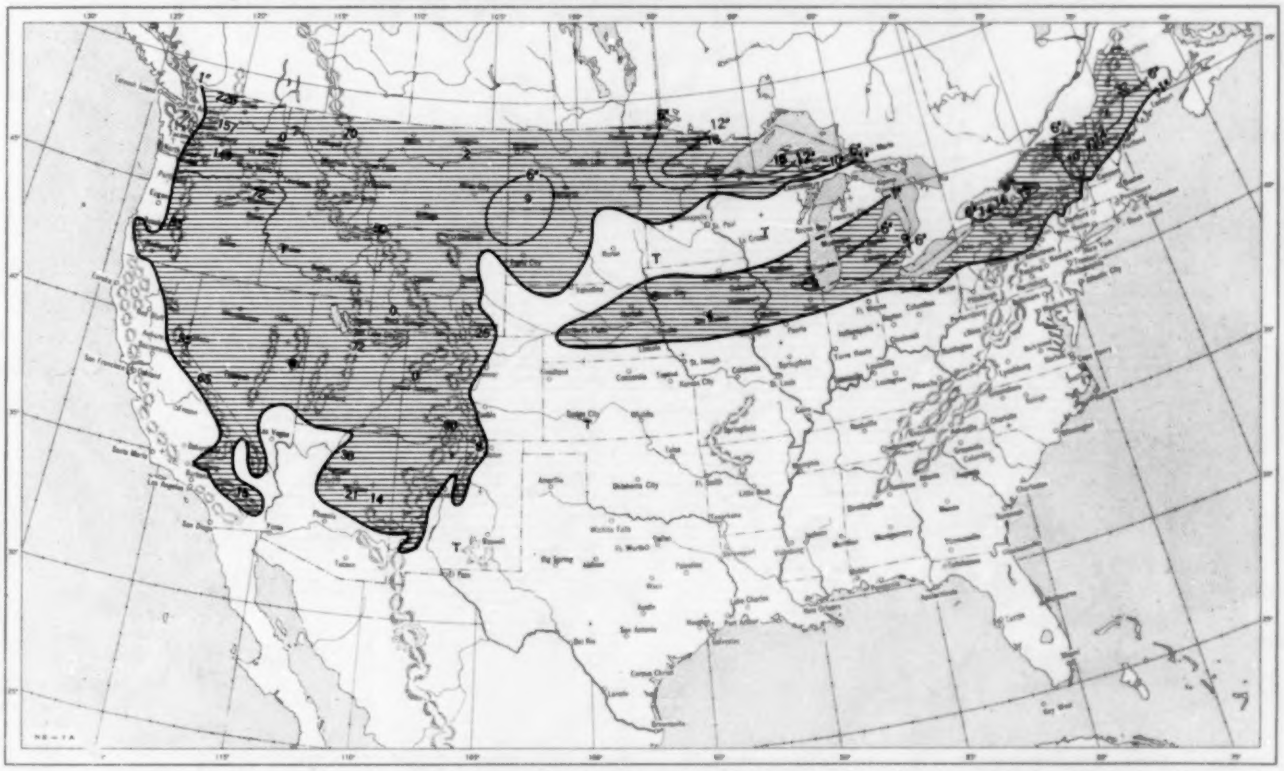


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, March 1954.

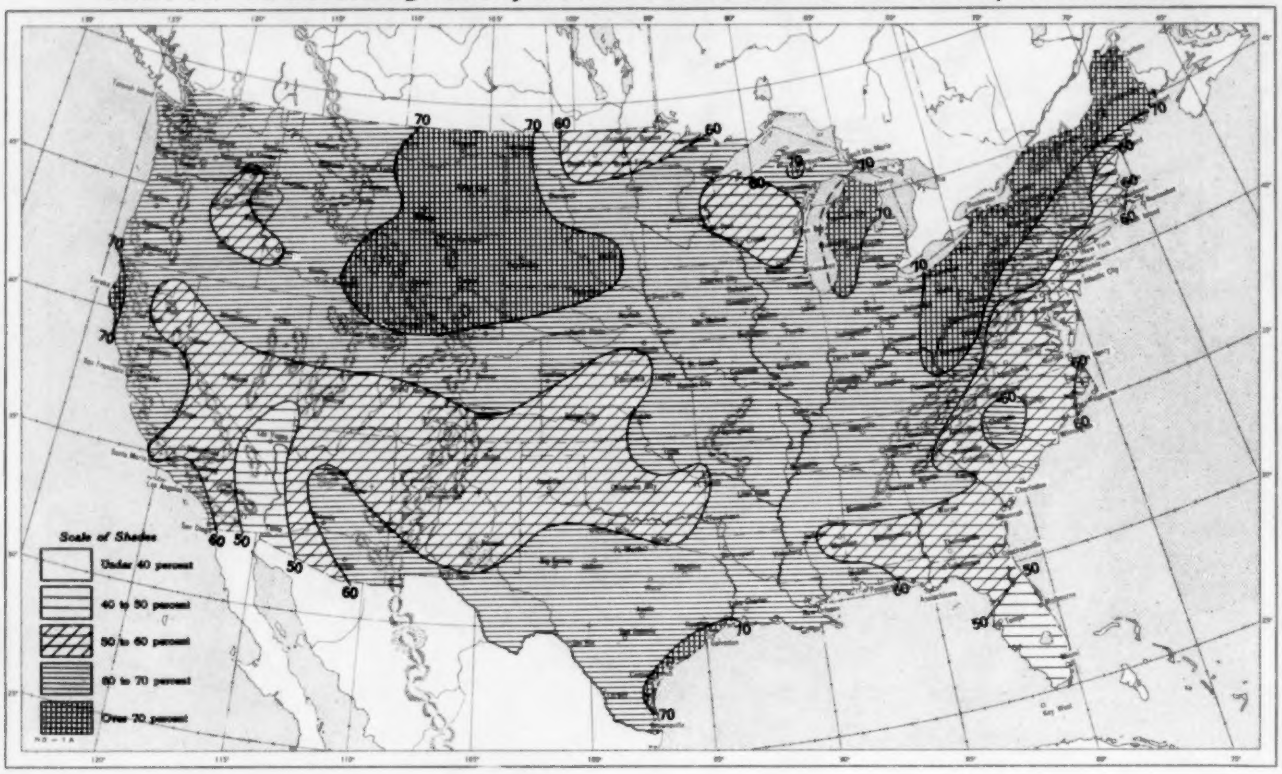


B. Depth of Snow on Ground (Inches), 7:30 a. m. E. S. T., March 30, 1954.

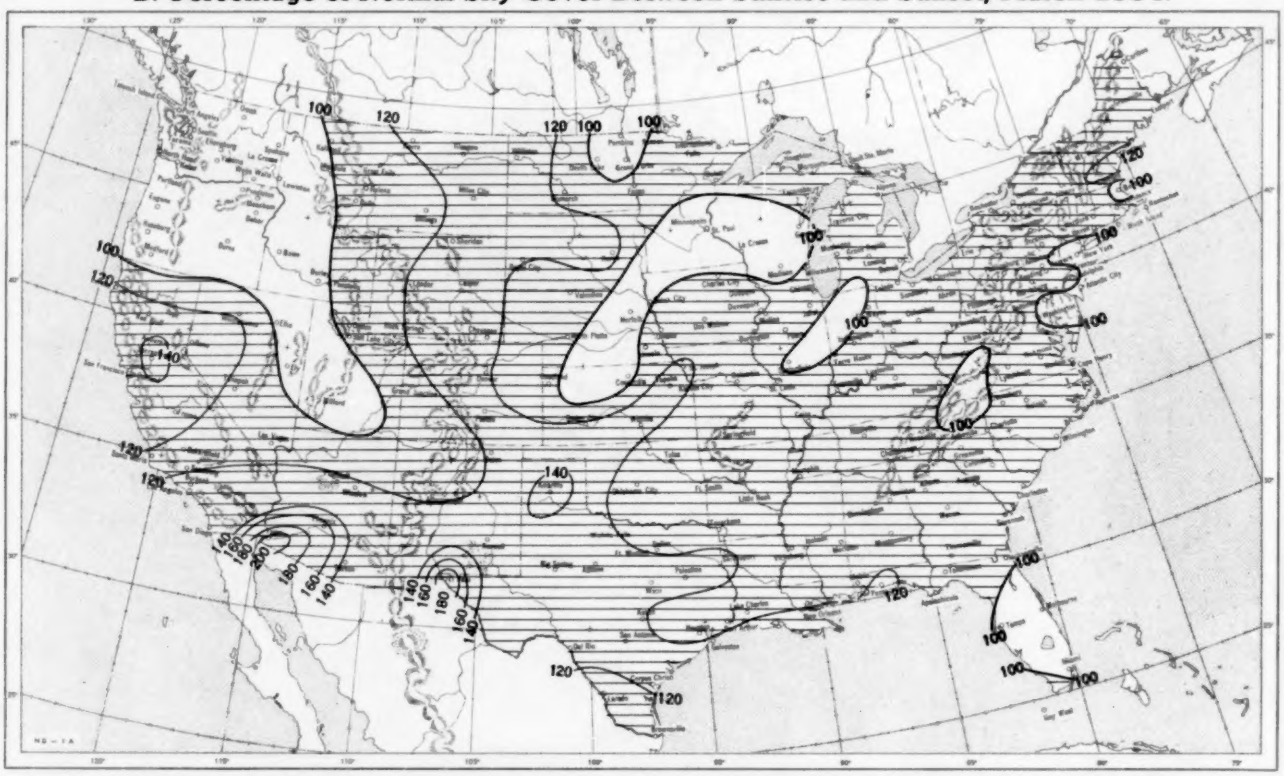


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, March 1954.

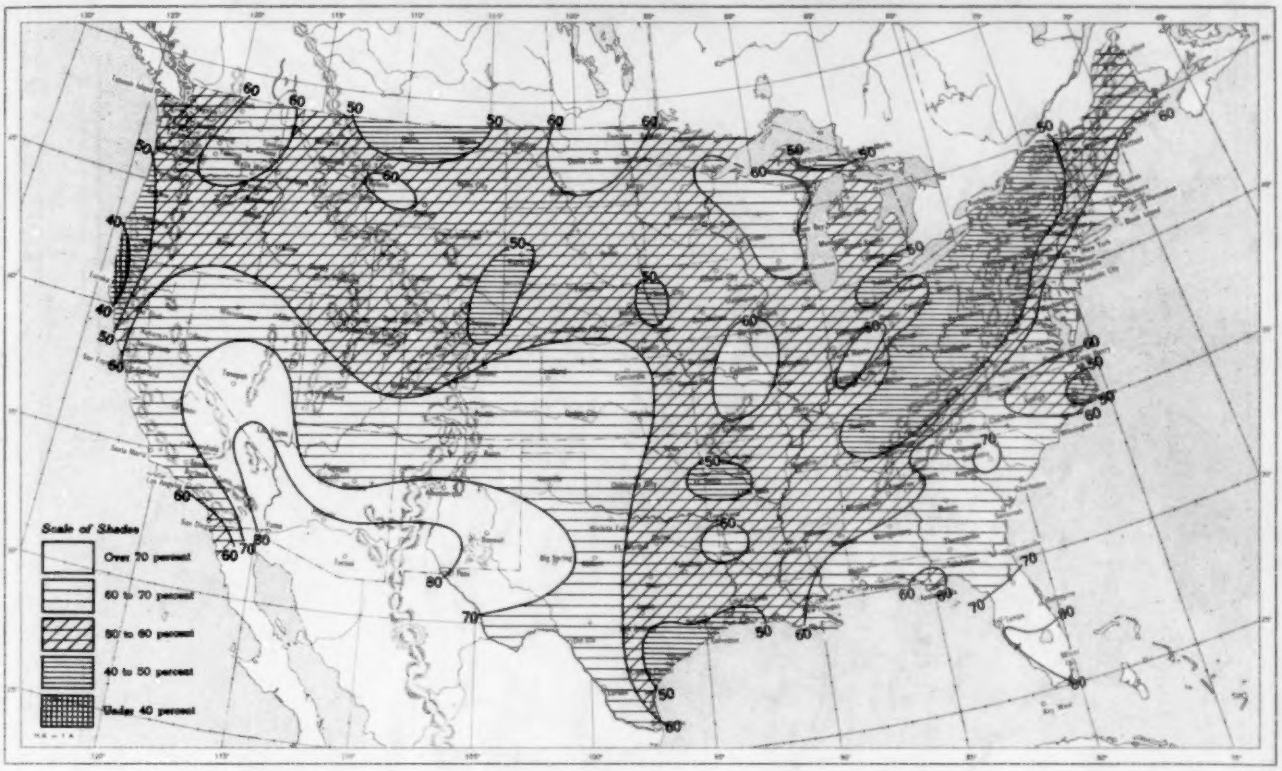


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, March 1954.

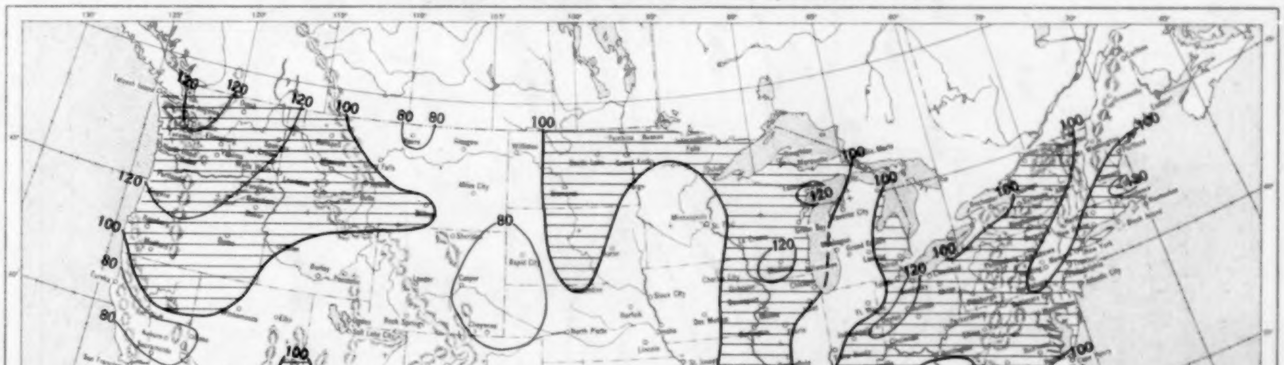


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, March 1954.



B. Percentage of Normal Sunshine, March 1954.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, March 1954. Inset: Percentage of Normal Average Daily Solar Radiation, March 1954.

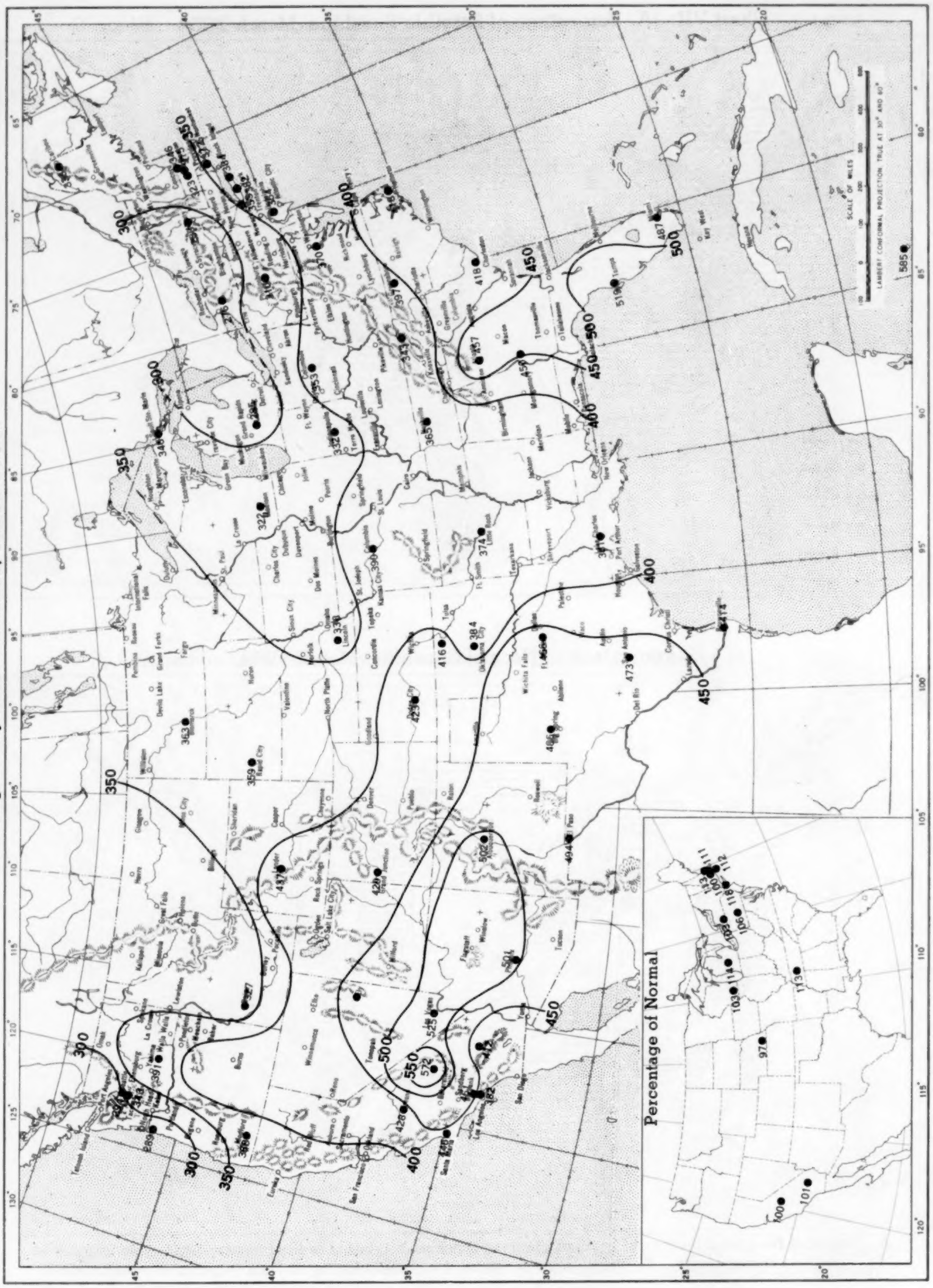
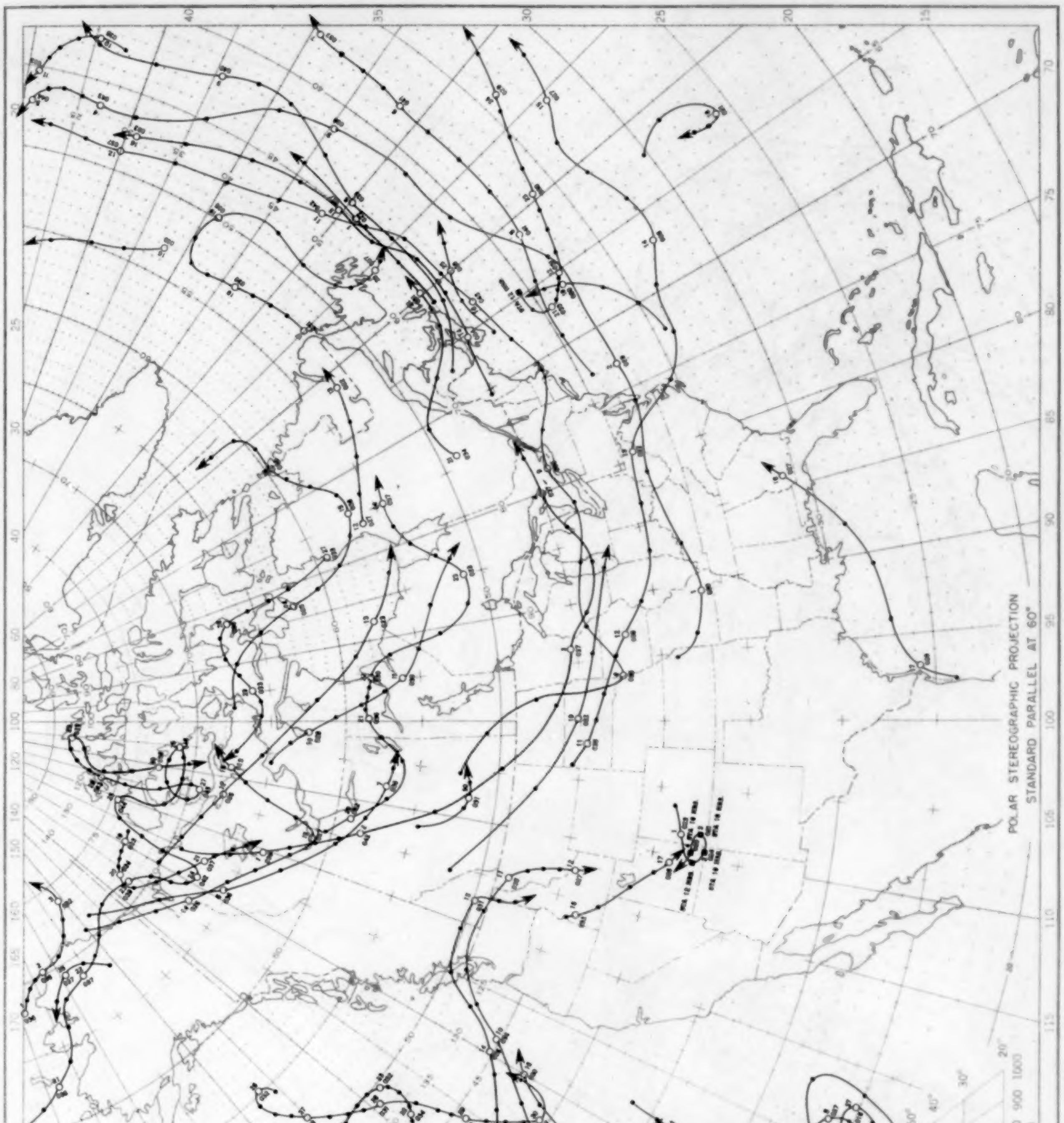


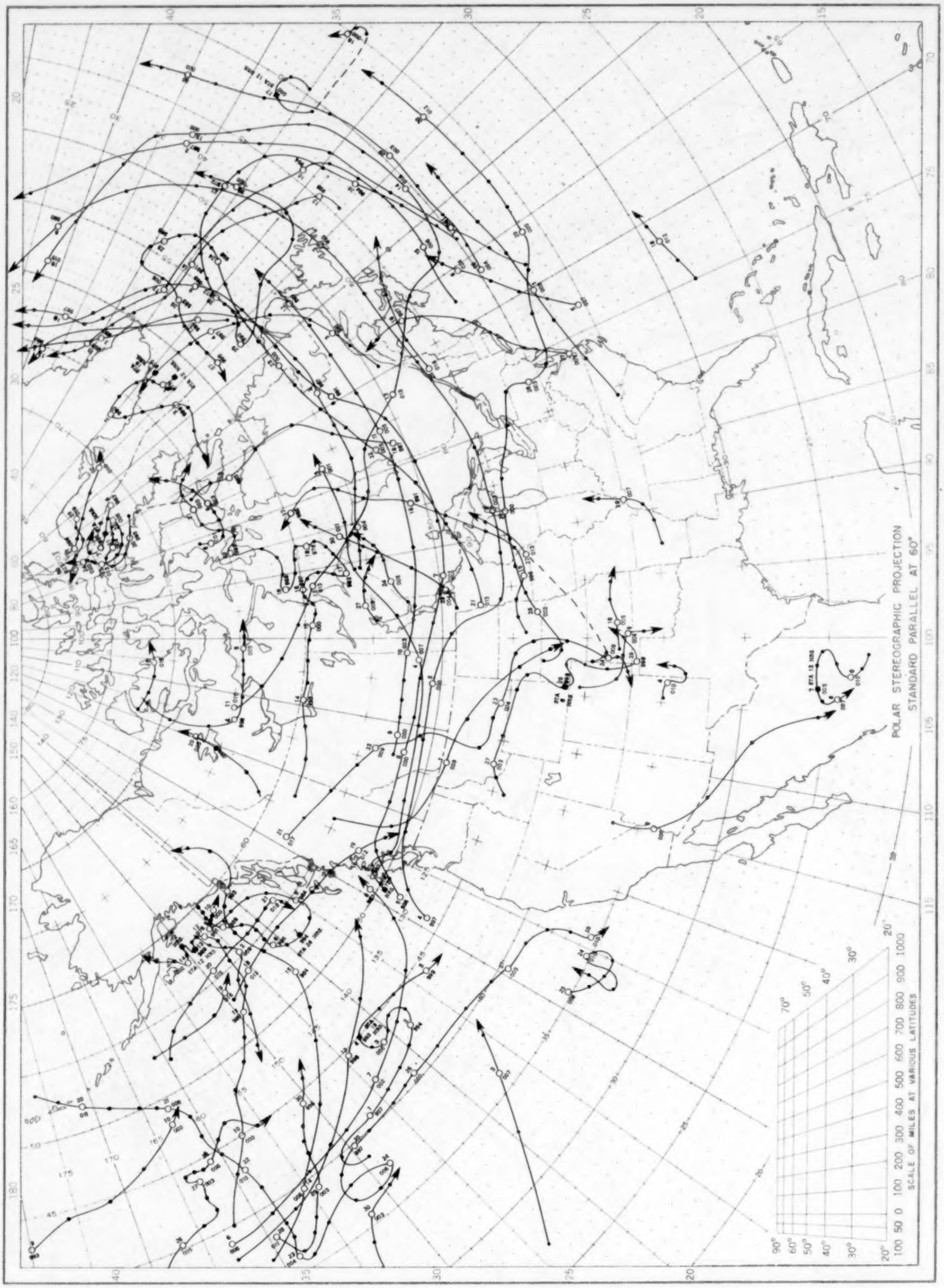
Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm.$^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown. Normals are computed for stations having at least 9 years of record.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, March 1954.



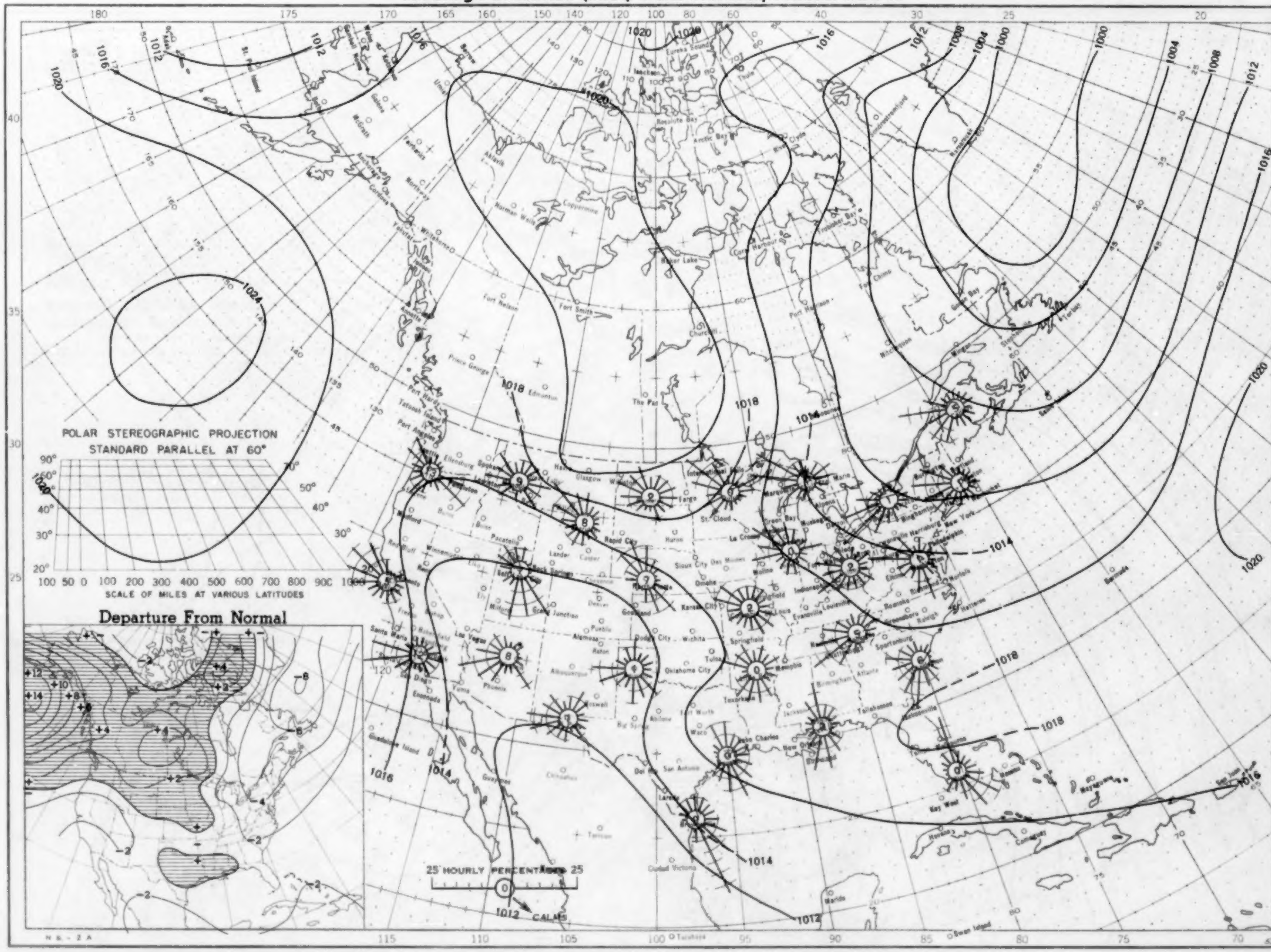
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, March 1954.



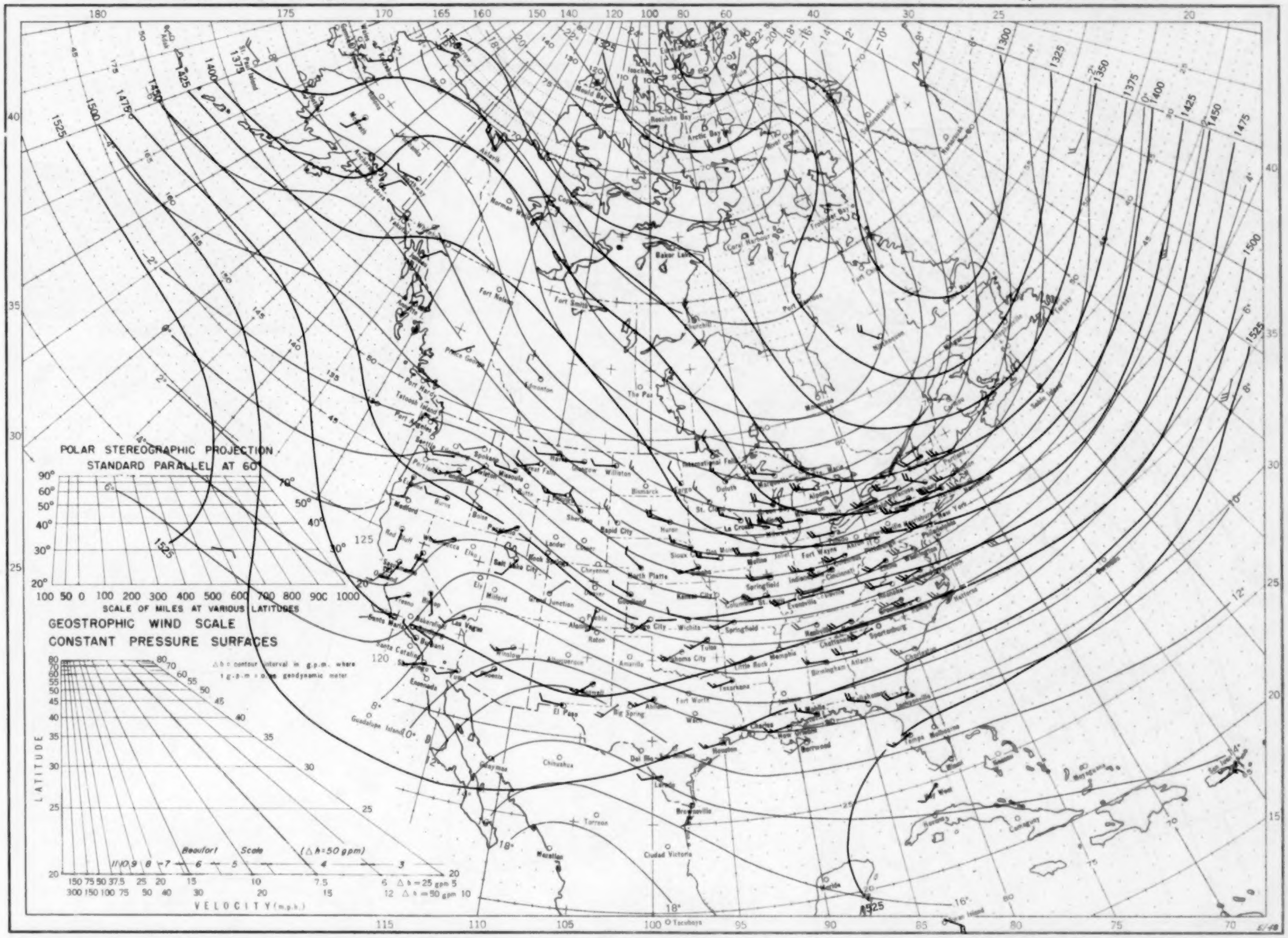
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, March 1954. Inset: Departure of Average Pressure (mb.) from Normal, March 1954.



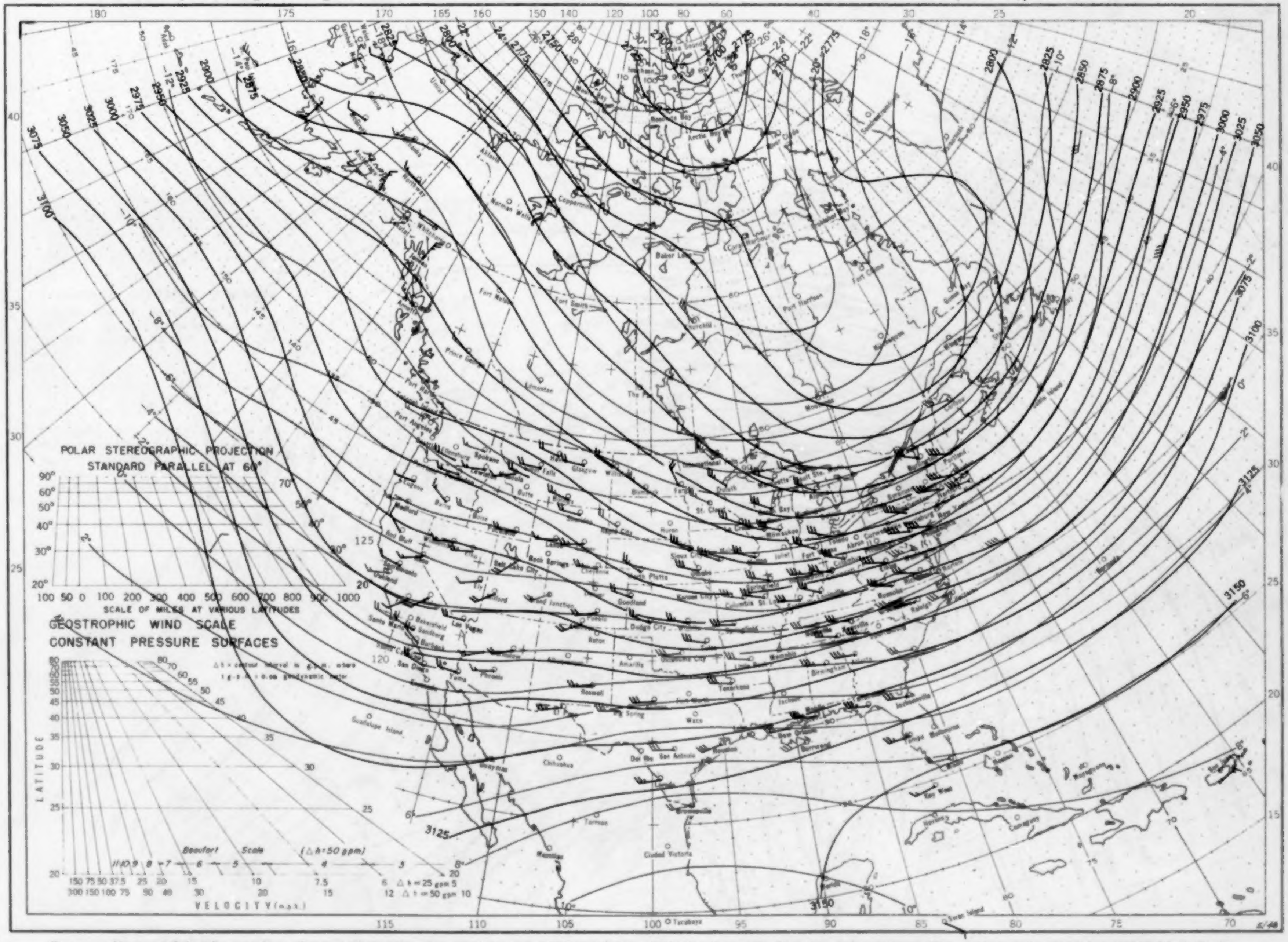
Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

Chart XII. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 850-mb. Pressure Surface, Average Temperature in °C. at 850 mb., and Resultant Winds at 1500 Meters (m.s.l.), March 1954.



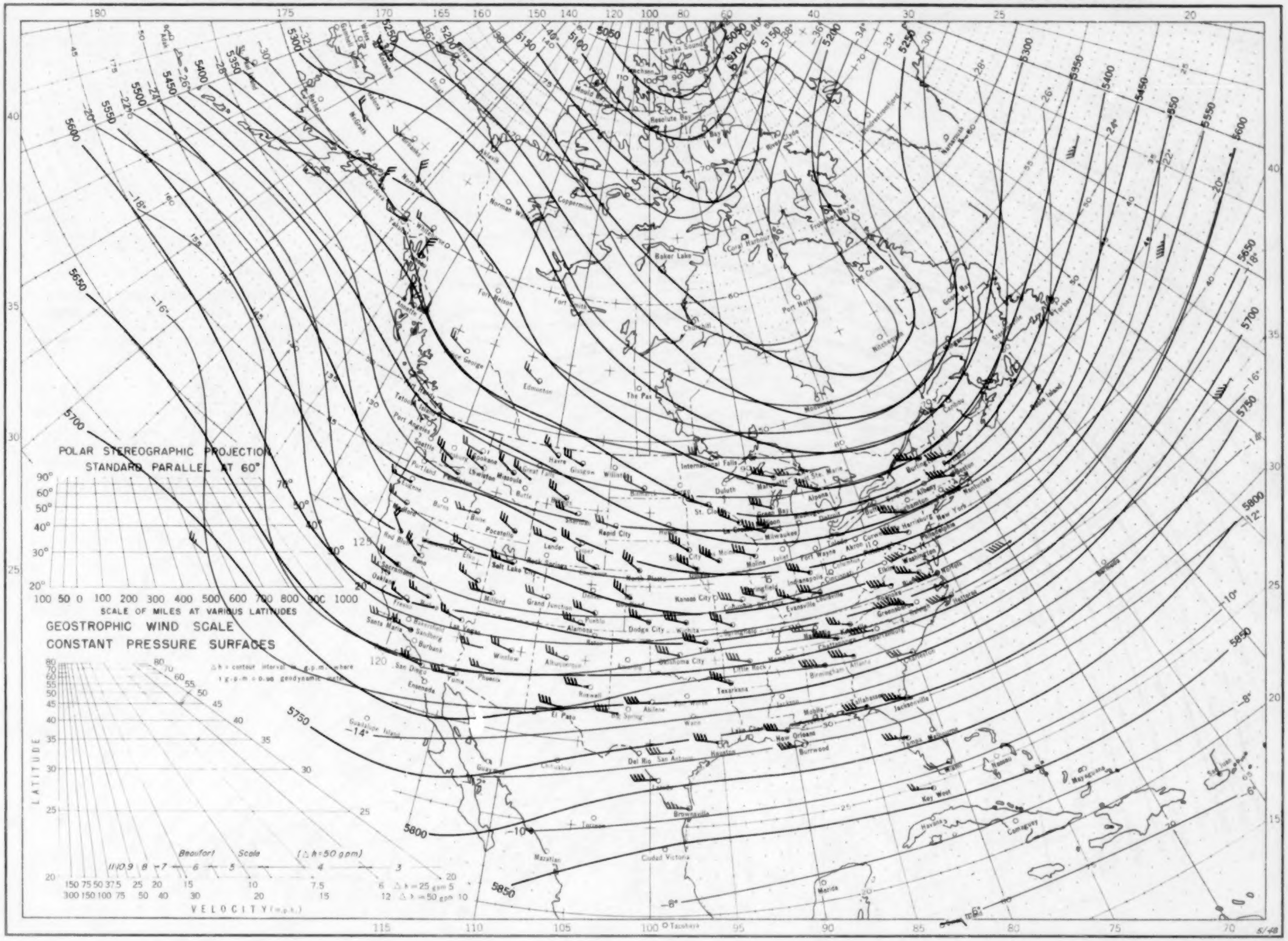
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIII. Average Dynamic Height in Geopotential Meters (1 g.p.m.. = 0.98 dynamic meters) of the 700-mb. Pressure Surface, Average Temperature in °C. at 700 mb., and Resultant Winds at 3000 Meters (m.s.l.), March 1954.



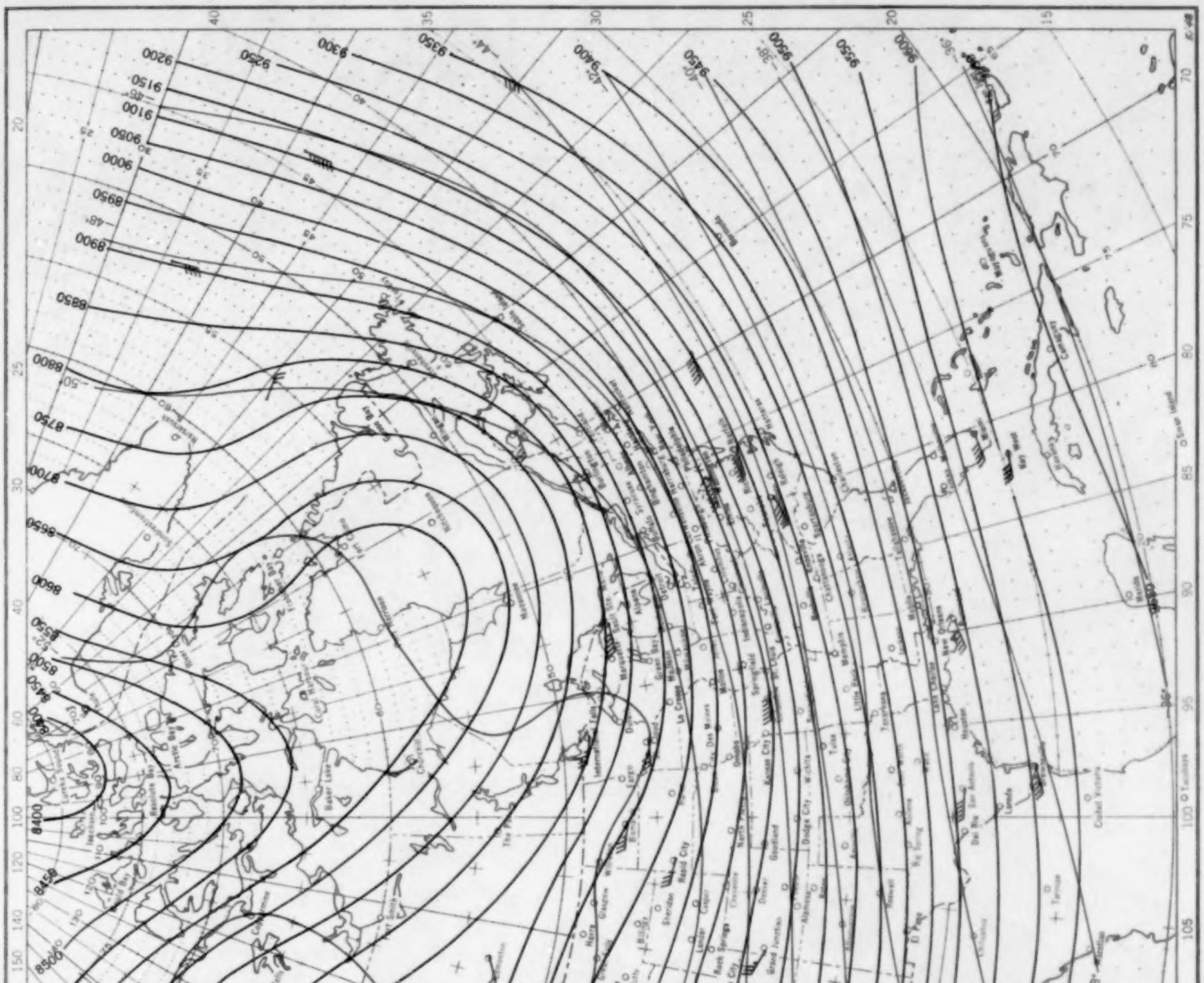
Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins taken at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XIV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 500-mb. Pressure Surface, Average Temperature in °C. at 500 mb., and Resultant Winds at 5000 Meters (m.s.l.), March 1954.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.

Chart XV. Average Dynamic Height in Geopotential Meters (1 g.p.m. = 0.98 dynamic meters) of the 300-mb. Pressure Surface, Average Temperature in °C. at 300 mb., and Resultant Winds at 10,000 Meters (m.s.l.), March 1954.



Contour lines and isotherms based on radiosonde observations at 0300 G. M. T. Winds shown in black are based on pilot balloon observations at 2100 G. M. T.; those shown in red are based on rawins at 0300 G. M. T. Wind barbs indicate wind speed on the Beaufort scale.